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ACTIVE TAMPING EXPERIMENTS

Final Report 131

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Submitted by: Dennis W. Baum, Stephen P. Gill, Robert F. Flagg, John D. Watson

ARTEC ASSOCIATES INCORPORATED
26046 Eden Landing Road
Hayward, California 94545
Telephone: 415/785-8080

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This study is an experimental investigation of an advanced explosive technique for improving the penetration and/or hole volume capabilities of shaped charge warheads. The technique is based upon using an inner and outer explosive layer in an otherwise conventional shaped charge configuration. The outer layer of explosive is chosen to have a slower detonation velocity than the inner. This produces a situation in the expanding detonation products where the rarefaction wave which originates at the

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outside wall, arrives at the centerline later in time than if the explosive load were uniform. In the present series of experiments which consisted of one shot of each configuration, an increase of almost 30 percent in penetration was obtained between the FMC loaded baseline case and the best FMC loaded test case. Because of the limited data, caution must be used in applying this increase to all cases, particularly when the Firestone loaded warheads show the same degree of difference from the baseline cases.

SUMMARY AND CONCLUSIONS

This document is a comprehensive final report of an experimental effort to investigate the effect of lateral surface boundary conditions on shaped charge performance. Included among the design variations was a novel "active" tamping concept proposed by Artec Associates.

The "active" tamping hypothesis simply stated is, if the outer layer of explosive of a shaped charge device is replaced by an explosive having a lower detonation velocity than the main charge, then the arrival of the head of the rarefaction wave at the liner outer surface, which signals the existance of the outer edge of the explosive is delayed. The liner collapse process then behaves as if the explosive were thicker than it is and yields jet parameters which would have otherwise required greater amounts of explosive.

The results of this preliminary experimental effort demonstrate that the lateral surface rarefactions significantly influence jet formation and the active tamping effect can be realized, although the conclusion is based on very limited data (essentially one data point).

Pivotal in the analysis of the data from seven experiments was the selection of a baseline run. It was our original intent to use the Firestone loaded warhead for this purpose, with a check using an otherwise identical FMC loaded device for confirmation. As the FMC device gave substantially different penetration and FMC's facilities loaded all of the experimental configurations, it was felt that using the FMC loaded standard round as baseline, would be more appropriate than using the Firestone loaded baseline round.

The test series demonstrated conclusively the improvement possible using heavy steel confinement, however such improvement is well-known in the field but impractical for prototype warheads since it required nearly 25 additional pounds of mass to produce this improvement.

The test series also demonstrated the improvement possible using massive additional explosive to provide confinement. Shot 131-5, the 10 pound Octol run, succeeded in increasing penetration by 37% over the FMC baseline round. Again, some improvement is to be expected since it required nearly 3 times the explosive to accomplish this improvement in penetration.

The test series verified that lateral surface rarefactions are of great importance in jet formation and that active tamping using TNT as the outer layer improved the penetration performance of the round by 27% in the present experiments.

The additional verification using a Baratol/Octol load, malfunctioned due to loading asymmetries and is not available for comparison.

Overall we would conclude based on limited but self consistant data that 30% improvement can be realized and what is equally important, the gain is founded on good physical grounds.

Preface

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The research reported in this report was sponsored by the Tactical Technology Office of the Defense Advanced Research Projects Agency. It was initiated under the auspices of Dr. E. Blase of that office and later by Dr. R. Gogolewski when he assumed Dr. Blase's duties.

The effort covered in this document was performed at ARTEC ASSOCIATES INCORPORATED, Hayward, California and their nearby test facility, by a task team composed of Dennis W. Baum, Stephen P. Gill, Robert F. Flagg and John D. Watson. Dr. Dennis Baum was the task leader and principal investigator.

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1. INTRODUCTION

In 1978, Artec Associates Incorporated proposed to DARPA a novel method for increasing the directed energy output of a shaped charge warhead, without increasing size or weight. We suggested that the outer steel casing of a shaped charge (or self-forging fragment) warhead and/or outer layers of explosive be replaced with an equivalent amount of low detonation velocity explosive, as shown in Figure 1.

This concept was originally conceived by Mr. L. Derrington, an explosive technician. He claimed experimental improvement in several unpublished experiments with shaped charges. The concept is indeed surprising at first glance and experimental claims were met with considerable scepticism by his co-workers.

On reviewing possible theoretical reasons for a performance increase with a layer of slow explosive, Artec found what we believe to be valid justification for the improvement based on wave propagation times in detonation products. We hypothesized, that the outer layer of lower detonation velocity explosive would provide "active tamping" by essentially delaying the arrival of rarefactions which normally are created at the tamper surface.

The likely result of a postponed arrival of the outside edge rarefaction is to increase the impulse to the imploding liner during the collapse process and hence to increase jet energy and penetration.

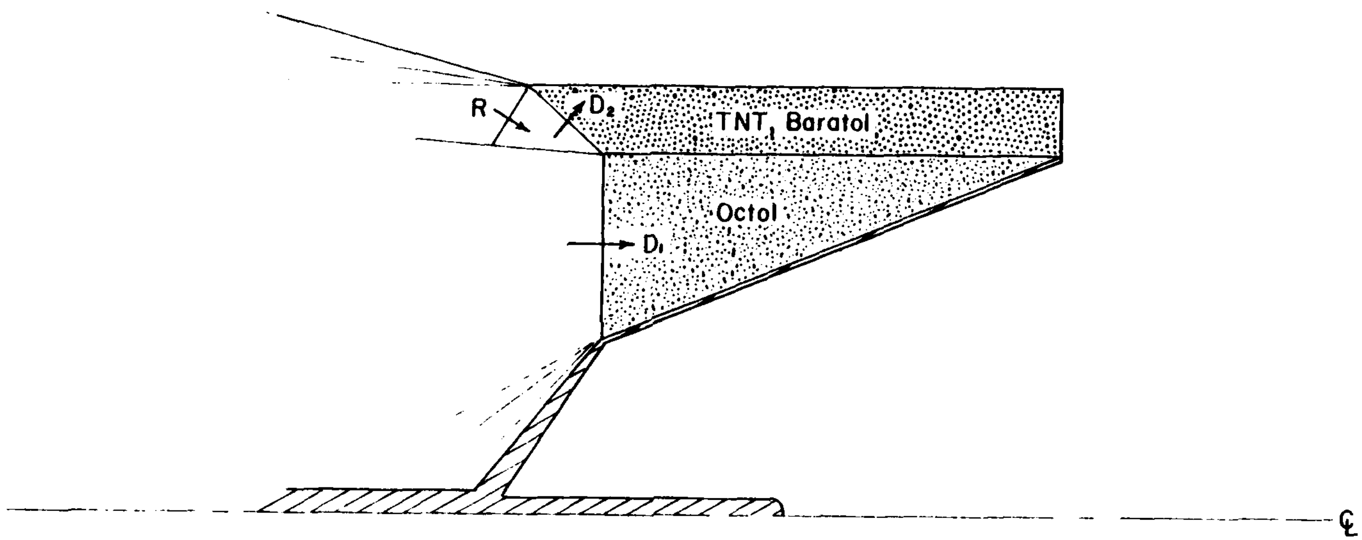


Figure I Schematic Operation of Explosively Tamped Shaped Charge

Based on this background, Artec proposed to DARPA a short exploratory series of tests, using an existing shaped charge warhead design to test the sensitivity of warhead performance to lateral effects and determine the validity of the concept. The results of the experiments and accompanying analysis are presented in this report.

2. THEORETICAL CONSIDERATIONS

From a theoretical point-of-view, this project is concerned essentially with improving the performance of high explosive devices by modifying boundary conditions. It should be appreciated that although a shaped charge was used as a test bed for the tamping concept, the concept may well be applied successfully to other explosive devices.

Ideally, the amount of energy delivered to a shaped charge liner is maximized by using a perfectly rigid, immovable tamper at the outside boundary, so that the volume available to the expanding detonation products is constrained.

As a practical matter for some weight limited weapon systems, it is not feasible to consider even a modest steel tamper on the warhead. A thin structural shell of a practical shaped charge is for all intents and purposes an untamped free surface, hence the explosive detonation products are free to expand outward as well as accelerate the liner cone inward. In turn, only a fraction of the explosive energy, depending on the local ratio of charge mass to liner mass (C/M ratio), is delivered to the liner. This behavior leads to diminished jet velocity and jet energy and therefore to reduced target penetration.

2.1 Rarefaction Waves in Detonation Products

The classical Chapman-Jouguet theory of detonation assumes that the sum of the local sound speed and particle velocity equals the detonation velocity, i.e.

$$D = U + C$$

where D is the detonation velocity, U the flow velocity, and C the sound speed of the detonation products.

In the simplest case of an infinitely long tube of explosive, the conditions behind the detonation wave are constant and $D = U + C$ everywhere in the absence of lateral boundary motion. Figure 2 depicts a situation in which rarefactions are introduced into the detonation products at discrete points a, b, c. The resulting rarefaction fronts A, B, C are always tangent to the detonation front; this physical result is a direct consequence of the Chapman-Jouguet theory.

A lateral free surface may be considered as an infinite sequence of rarefaction centers in a straight line. As the leading rarefaction head immediately follows the detonation, there is no region of undisturbed flow. This situation is shown schematically in Figure 3a.

It is recognized that in addition to the rarefaction from the side boundary that we are discussing here, there is also a rarefaction from the rear boundary (the Taylor rarefaction). As a consequence of the Chapman-Jouguet condition the head of the rear boundary rarefaction travels with the detonation front. We primarily concerned ourselves in this program with the side rarefactions since that is likely to be stronger in a shaped charge configuration.

Tamping acts to delay the rarefaction from the free surface, as shown in Figure 3b. The passing detonation transmits a strong shock wave into the tamper and reflects from the outer

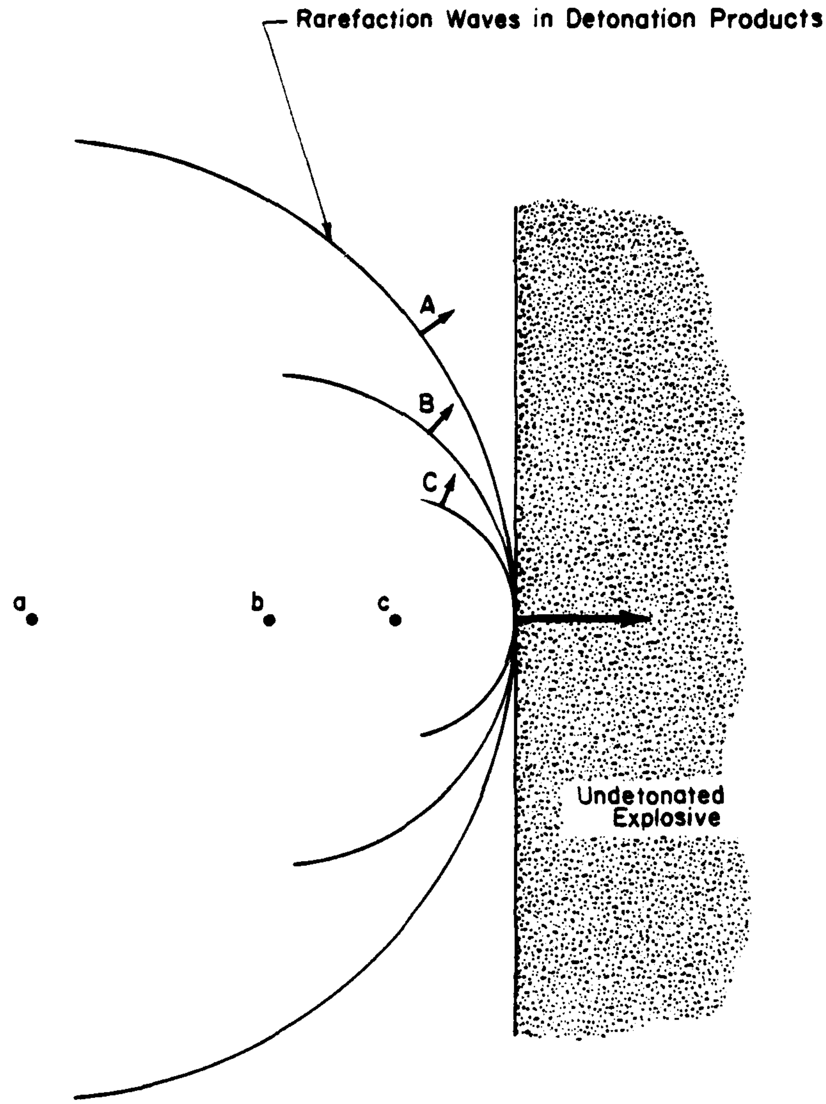
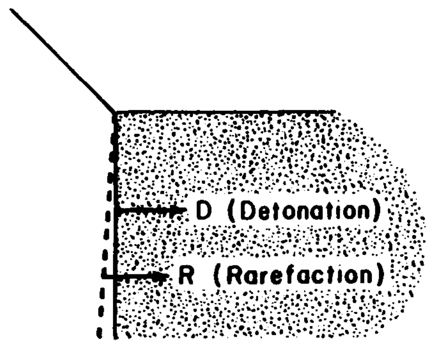
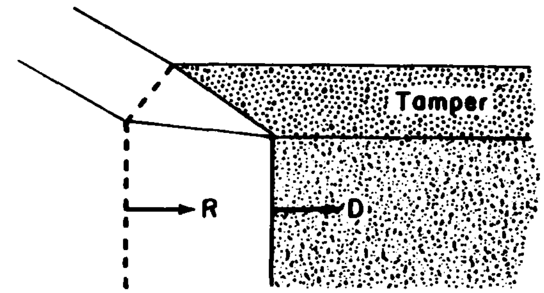


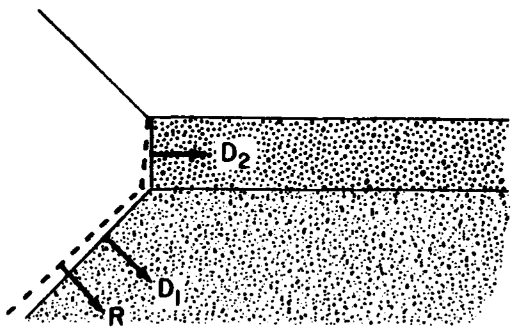
Figure 2 Rarefaction Wave Phenomena in Chapman-Jouget Detonations



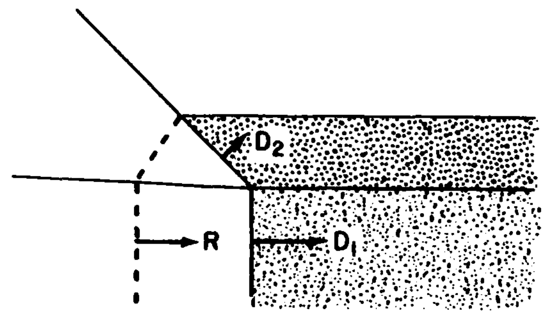
a) Untamped Explosive



b) Tamped Explosive



c) Explosive with High Velocity Outer Layer



d) Explosive with Low Velocity Outer Layer

Figure 3 Rarefaction Front Propagtion for Various Configurations free surface as a rarefaction wave. After transiting back through the tamper, the rarefaction enters the detonation gases. Because of the Chapman-Jouguet condition, the forward velocity of the rarefaction equals the detonation velocity, and never catches up with the detonation front. Thus there is a region of high pressure behind the detonation front before the arrival of the free surface rarefaction. There is of course a reduction from Chapman-Jouguet detonation pressures due to the finite impedance of the tamper material, but this is relatively small compared to the free surface rarefaction effect.

For a two-layer explosive system with a fast outer layer the rarefaction wave immediately follows the detonation wave, as shown in Figure 3c. This configuration is not an advantageous one from the point of view of rarefaction propagation.

Conversely, for a two-layer explosive system with a slow outer layer, the leading rarefaction lags the detonation front, as shown in Figure 3d. The delay in rarefaction arrival from a slow explosive layer is similar to that from a tamper, which is what makes the concept interesting from a practical point-of-view.

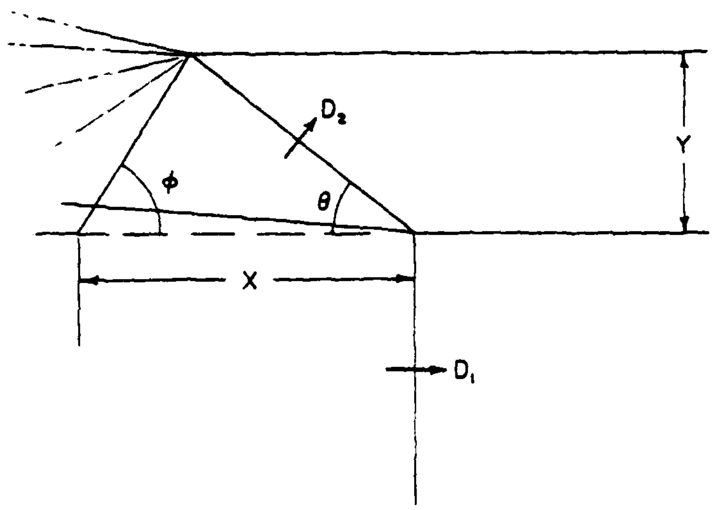
It is not intuitively obvious that the rarefaction front is delayed by a slow explosive, which is undoubtedly the reason slow explosives have not been considered before. However, the result follows directly from a Huygens wave construction of rarefaction propagation on applying the Chapman-Jouguet theory to each explosive layer.

Another way of interpreting the situation is to consider a frame of reference fixed on the fast detonation wave in the main charge. In this frame of reference the Chapman-Jouguet condition in the main charge is equivalent to stating that the flow Mach number is unity. The oblique detonation front in the slow explosive, on the other hand, has a Mach number greater than one, and a corresponding Mach angle of rarefaction propagation less than 90 degrees.

Given the properties of the two explosive layers, the relative angles and rarefaction wave locations may be worked out, as shown in Figure 4. Here, γ_2 is an equation of state parameter of the slow explosive (ratio of enthalpy to energy in the Chapman-Jouguet state).

One may also determine the effective impedance of a slow explosive layer compared to a tamper by matching interface conditions, as shown in Figure 5. TNT and Baratol are seen to be roughly comparable to steel, with interface pressures about 250 kbar. TNT is slightly stiffer, and Baratol slightly softer, but the differences are minor compared with the rapid falloff to atmospheric pressure of a free surface.

In our early evaluations of the merits of slow explosive layers we calculated wave diagrams for a steel tamper and an equal mass of TNT or Baratol over Octol. The results are shown in Figure 6. It may be seen from the figure that the explosive layers are substantially better in delaying the rarefaction than an equal mass of steel tamper, with Baratol being about 18% more effective than TNT.



$$1)\quad \sin\theta = \frac{D_2}{D_1}$$

$$2)\quad \frac{\sin\theta}{\sin\phi} + \frac{1}{\gamma_2 + 1}\cos(\theta+\phi) - \frac{\gamma_2}{\gamma_2 + 1} = 0$$

$$3)\quad X = Y\left(\frac{1}{\tan\phi} + \frac{1}{\tan\theta}\right) = D_1\,\tau$$

Figure 4 Detonation and Rarefaction Wave Configuration for Explosive Tamping

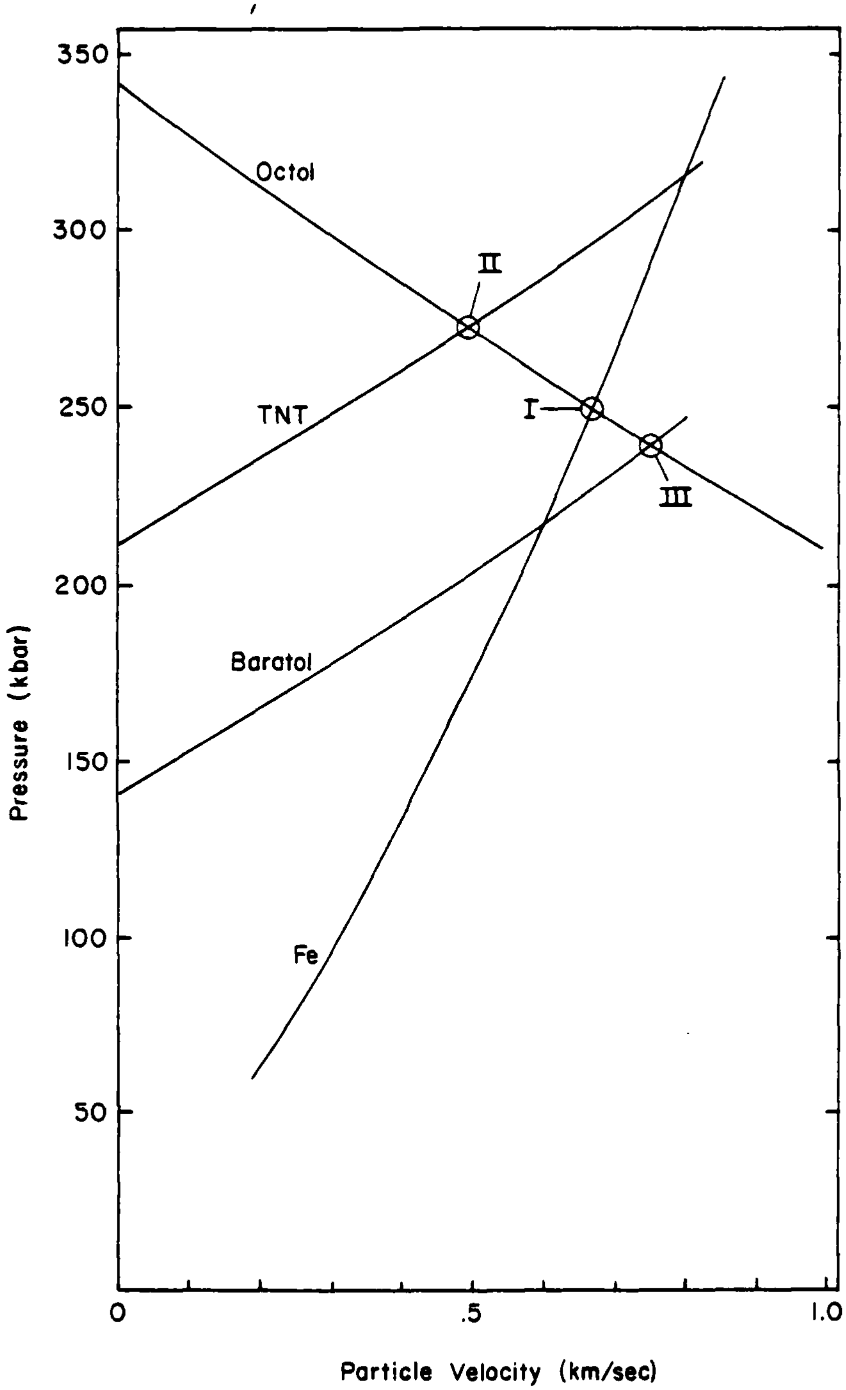


Figure 5 P-U Plane Method for Determining Interface Conditions

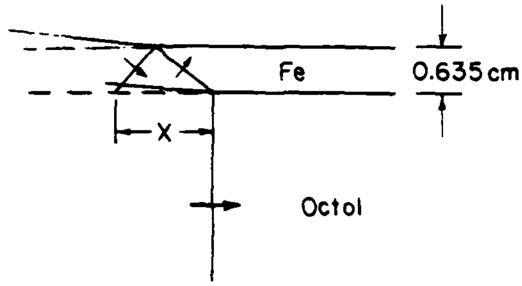
Case I

ϕ = 49.8°

θ = 38.6°

X = 1.33cm

τ = 1.57μsec



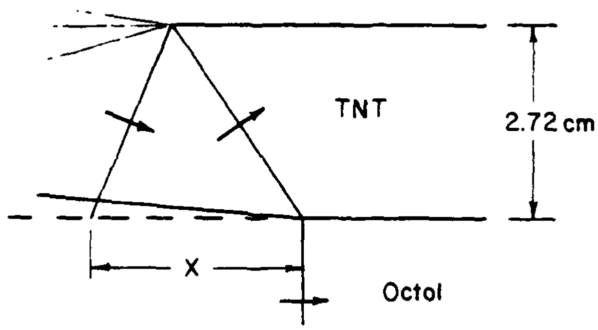
Case II

ϕ = 68.2°

θ = 54.8°

X = 3.01cm

τ = 3.55μsec



Case III

ϕ = 57.9°

θ = 38.8°

X = 3.56cm

τ = 4.19μsec

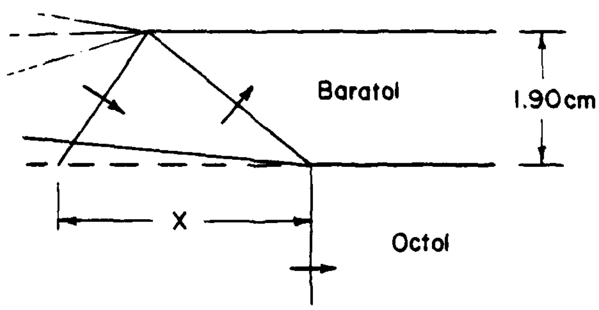


Figure 6 Wave Diagrams for Constant Tamper Mass

To summarize, a slow explosive layer on the outside of a faster one acts to significantly delay the rarefaction from the side boundary. It is presumed that this leads to a higher impulse to the liner during the collapse process. This would provide the effect of a heavy tamping material when needed, i.e. during the collapse process.

It requires experimental work or considerably more involved finite-difference calculations than this simple analysis to determine quantitatively how much shaped charge performance will be modified by the boundary condition modification and the extent of application in a practical warhead.

3. EXPERIMENTAL CONSIDERATIONS

3.1 General Considerations

Seven experiments covering a range of configurations were planned and executed in this effort. The parameters of interest for each experiment are tabulated for comparison in Table 1 and discussed individually below. As can be seen from the table, Octol, Octol/TNT and Octol/Baratol loadings were used with explosive weights ranging from the nominal standard 3.5 lbs. (1.59 Kg) load to a 10 lb. (4.5 Kg) load. Table 2 is a tabulation of the pertinent properties of these explosives for reference.

Two warheads were loaded by Firestone Corporation and were representative of production warheads. The remaining 5 warheads were loaded by FMC-Hollister. Standard RP-1 detonators were used to initiate each warhead.

All of the experiments except one used low density styrofoam sheets with hole cutouts appropriately placed, at either end of the charge for support. Previous experiments have shown that this symmetrical, low mass support does not affect the dynamics of the detonation and collapse. The thick walled shot (131-6) used wooden supports.

The warheads were spaced 15 centimeters from a 5 centimeter thick blast shield and fired through a nominal 6-inch diameter port into the diagnostic range.

Target location was 203.2 centimeters (20 cone diameters) to provide adequate spacing for jet diagnostics, although most

TABLE 1

EXPERIMENTAL PARAMETERS

Shot No.	Explosive	Explosive Weight	Loaded by	Purpose
131-1	Octol	1.59 Kg (3.5 lbs)	Firestone	Baseline
131-2	Octol	1.59 Kg (3.5 lbs)	FMC	FMC Baseline
131-3	Octol/TNT	1.59 Kg (3.5 lbs)	FMC	Active Confinement
131-4	Octol/Baratol	1.59 Kg (3.5 lbs)	FMC	Active Confinement
131-5	Octol	4.5 Kg (10 lbs)	FMC	Thick HE Confinement
131-6	Octol	1.59 Kg (3.5 lbs)	FMC	Thickwall Confinement
131-7	Octol	1.59 Kg (3.5 lbs)	Firestone	Repeat Baseline

TABLE 2*

PROPERTIES OF SOME COMMON

MILITARY EXPLOSIVES

	ΔH_{det} (Kcal/gram)	D (Km/sec at g/cc)	T_{melt} (°C)
TNT	1.29	6.93 @ 1.64	80.9
Octol	1.43	8.48 @ 1.81	79.80°
Baratol	0.72	4.87 @ 2.55	79.80°

*from Ref. 4.

prototype shots of this configuration occur at a standoff of only 6 cone diameters. The jet of a standard round has been determined, from other studies, to commence breakup at approximately 8 cone diameters.

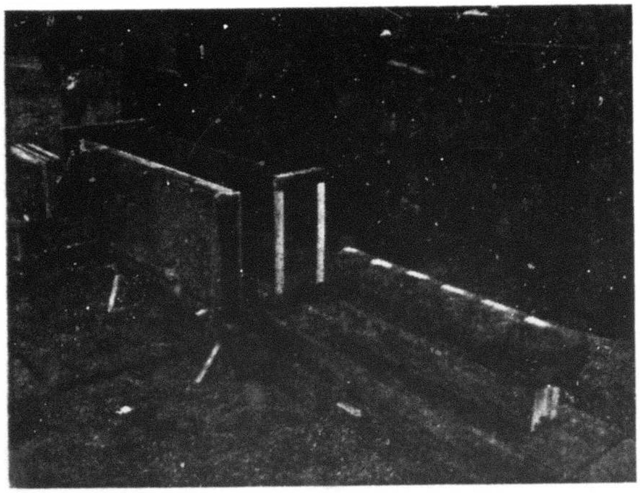
3.2 Description of the Experiments

The overall set up for the shots was common to all seven shots. Figure 7a shows the stack of 6 inch long, 6 inch diameter target blocks and the large cassette which contains the plates for the Cobra x-ray photographs. One Cobra x-ray head can be seen near the top right corner of Figure 7a. Figure 7b shows the styrofoam support jig, the blast shield and the cassette for the 1 MeV x-ray shots. The general arrangement, technique and operation are typical of explosive research test procedures.

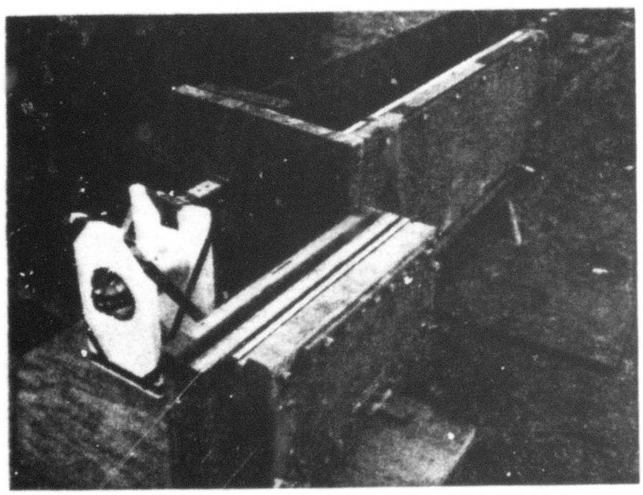
Shot 131-1

This shot, which was to be used as a baseline shot with which to compare the others, was a 3.5 lb (1.5 Kg) Octol round loaded by Firestone. The specific geometry, which is shown in Figure 8, included a 42° copper cone 4 inches in diameter and an aluminum outercase.

The target was spaced 203.2 cm (80 inches) from the warhead front face and the 2.5 cm rod grid in the 1 MeV x-ray was spaced 2.0 cm from the warhead front face. The first vertical gridmark for the Cobra x-rays (:) was spaced 50 centimeters from the front face.



a) Downrange view showing targets and flash x-ray cassette



b) Warhead end view showing warhead in place and 1 MeV cassette

Figure 7. Photographs of a Typical Test Configuration

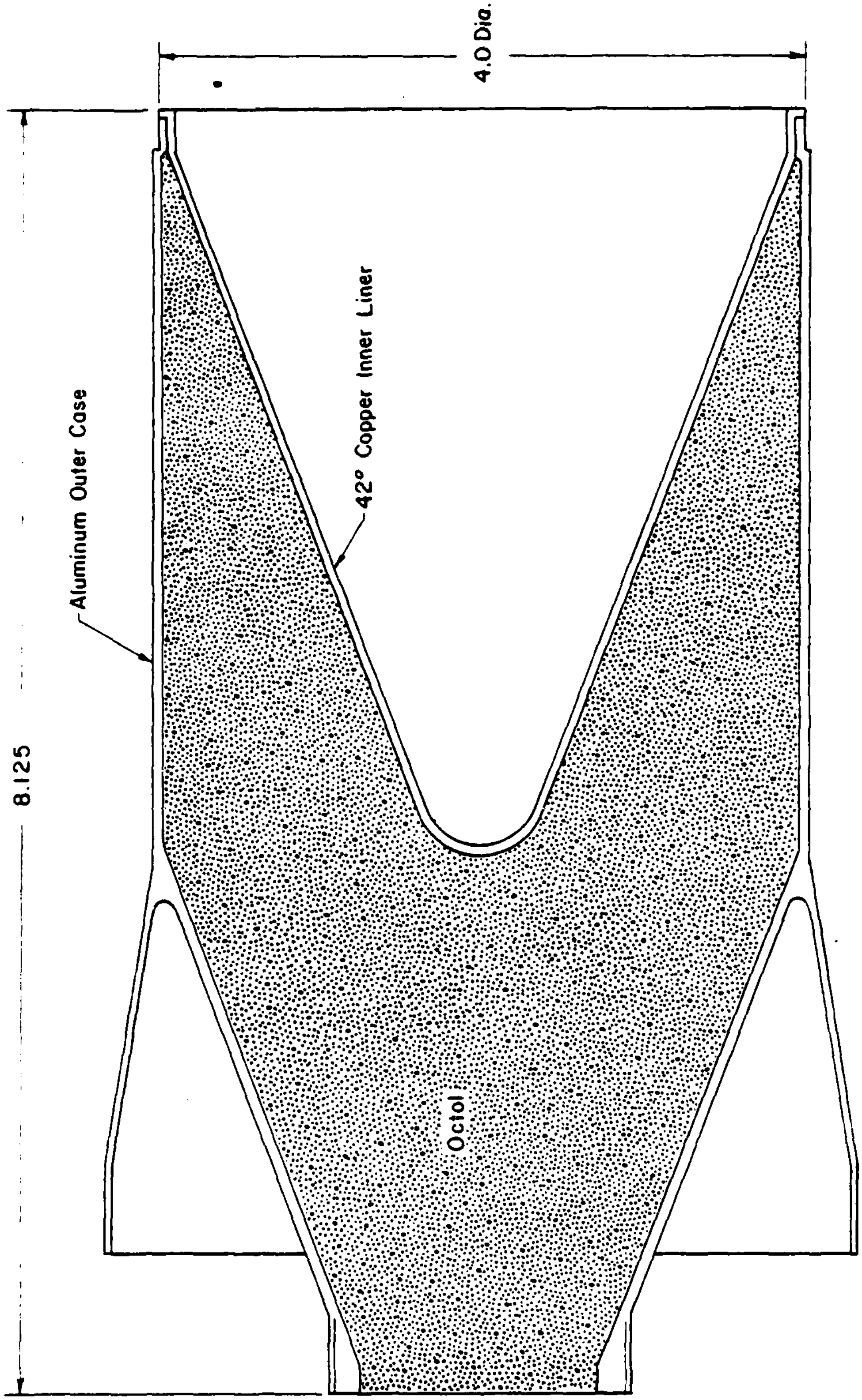


Figure 8 DRAGON Warhead

Shot 131-2

This experiment was a 1.5 Kg (3.5 lb) Octol round, loaded by FMC-Hollister. It was essentially identical to the Firestone baseline round but loaded by FMC and was fired to compare the effect of two loading facilities, which we had expected to be identical.

The target spacing was slightly different from 131-1, 203.2 cm (80 inches) as before, but the 2.5 cm rod grid for the 1 MeV x-rays was placed with 1 rod coincident with the front surface of the warhead and the first Cobra x-ray vertical grid mark (:) was spaced 51.15 cm from the warhead front face. The warhead geometry was similar to that shown in Figure 8.

Shot 131-3

This experiment used a 1.5 Kg (nominal 3.5 lb) Octol/ TNT explosive load and was loaded by FMC-Hollister. Its purpose was to test the two layer explosive hypothesis. The geometry is shown in Figure 9.

The target and grids spacing were as in shot 131-1. A special mandrel was fabricated and the Octol inner explosive cast first in this fixture. It was then inserted into the aluminum outercase and the TNT outer layer poured next. The closeness of the melting points of the two explosives (see Table 2) requires very close attention to pouring temperatures and procedures if the second pouring is to be prevented from melting the first. The results indicated that the pour was accomplished as designed.

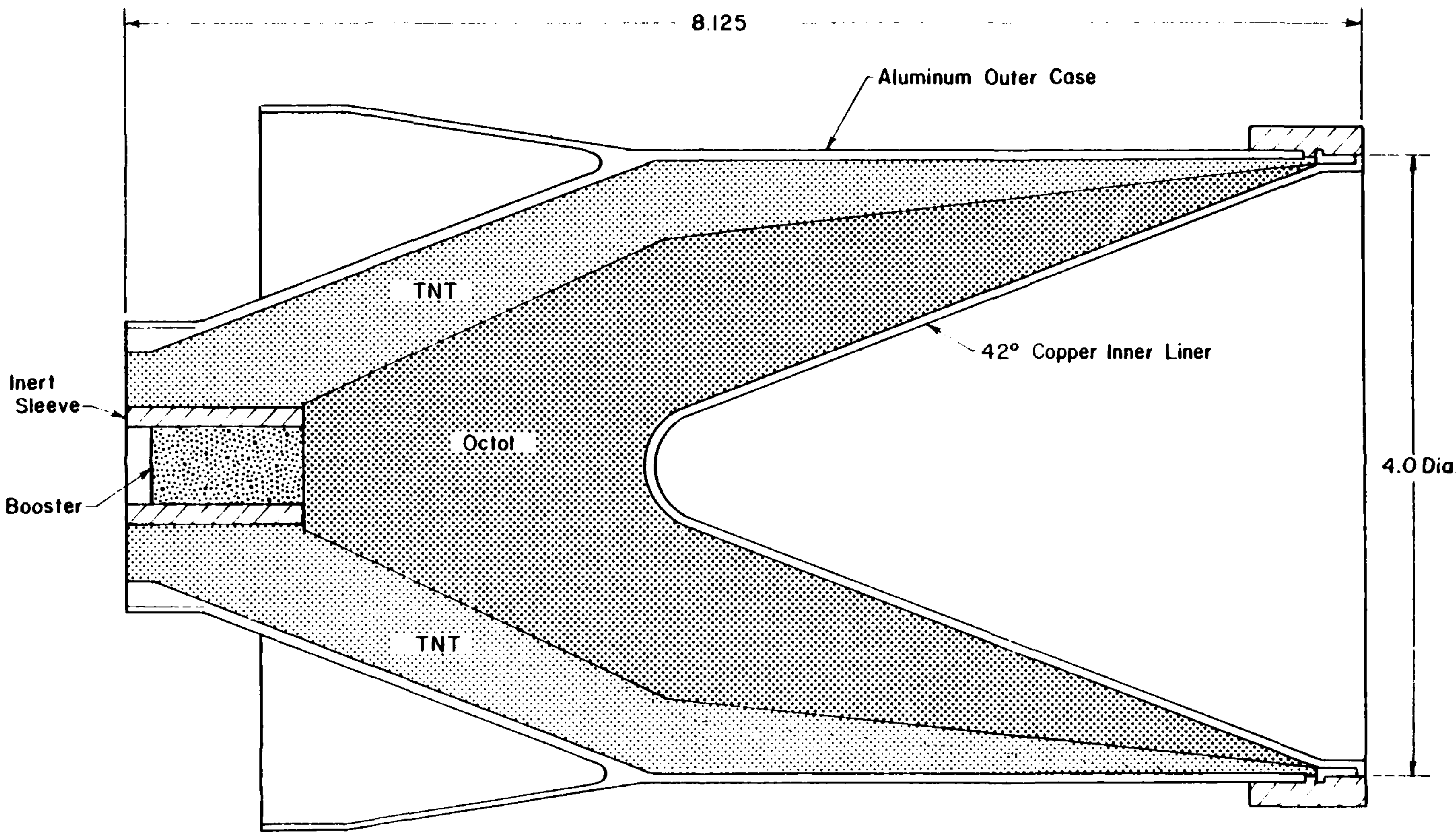


Figure 9 Shot 131-3, DRAGON Modified with TNT Outer Layer

Shot 131-4

This experiment used a 1.5 Kg (nominal 3.5 lb) Octol/ Baratol explosive load and was loaded by FMC-Hollister. The configuration is shown in Figure 10. Its purpose was to provide another test similar to Shot 131-3 but with a different explosive and hence provide additional data for the dual layer explosive hypothesis. The target and grid spacings were identical with 131-1.

In this case the detonation velocity of the Baratol is substantially different from the Octol so that the effects should be more pronounced and easily identifiable. Again the melting temperatures of the two materials are seen to be very close and considerable care is required to prevent the second pour melting and mixing with the first. As will be discussed later this pour was not accomplished according to design.

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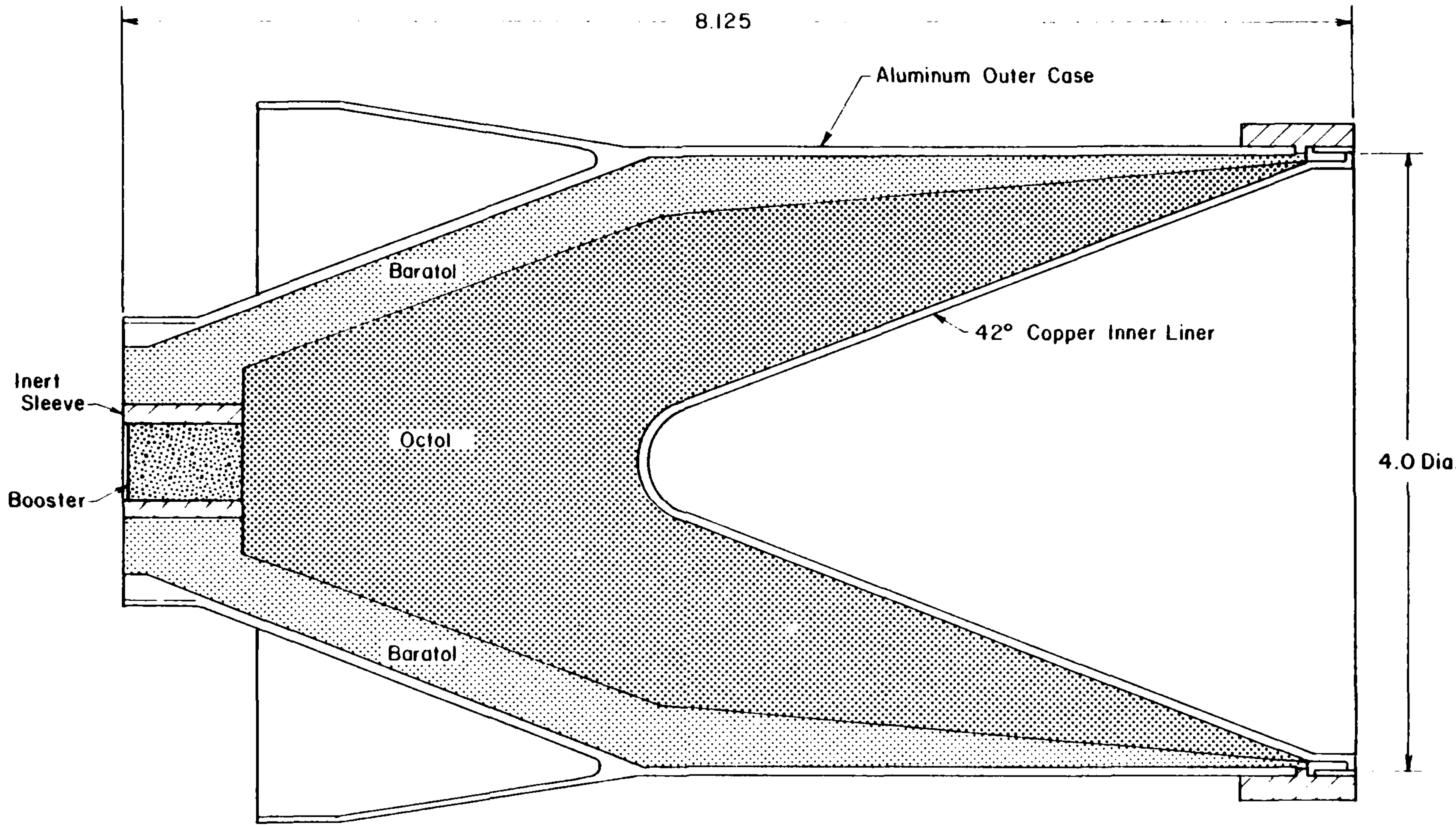

Figure 10 Shot 131-4, DRAGON Modified with Baratol Outer Layer

Shot 131-5

This experiment which had as its purpose to examine the effect of massive single component explosive confinement, used 4.54 Kg (nominal 10 lbs) of Octol explosive. The geometry for this run is given in Figure 11.

The target, rod grid and range grid spacings were identical to Shot 131-1.

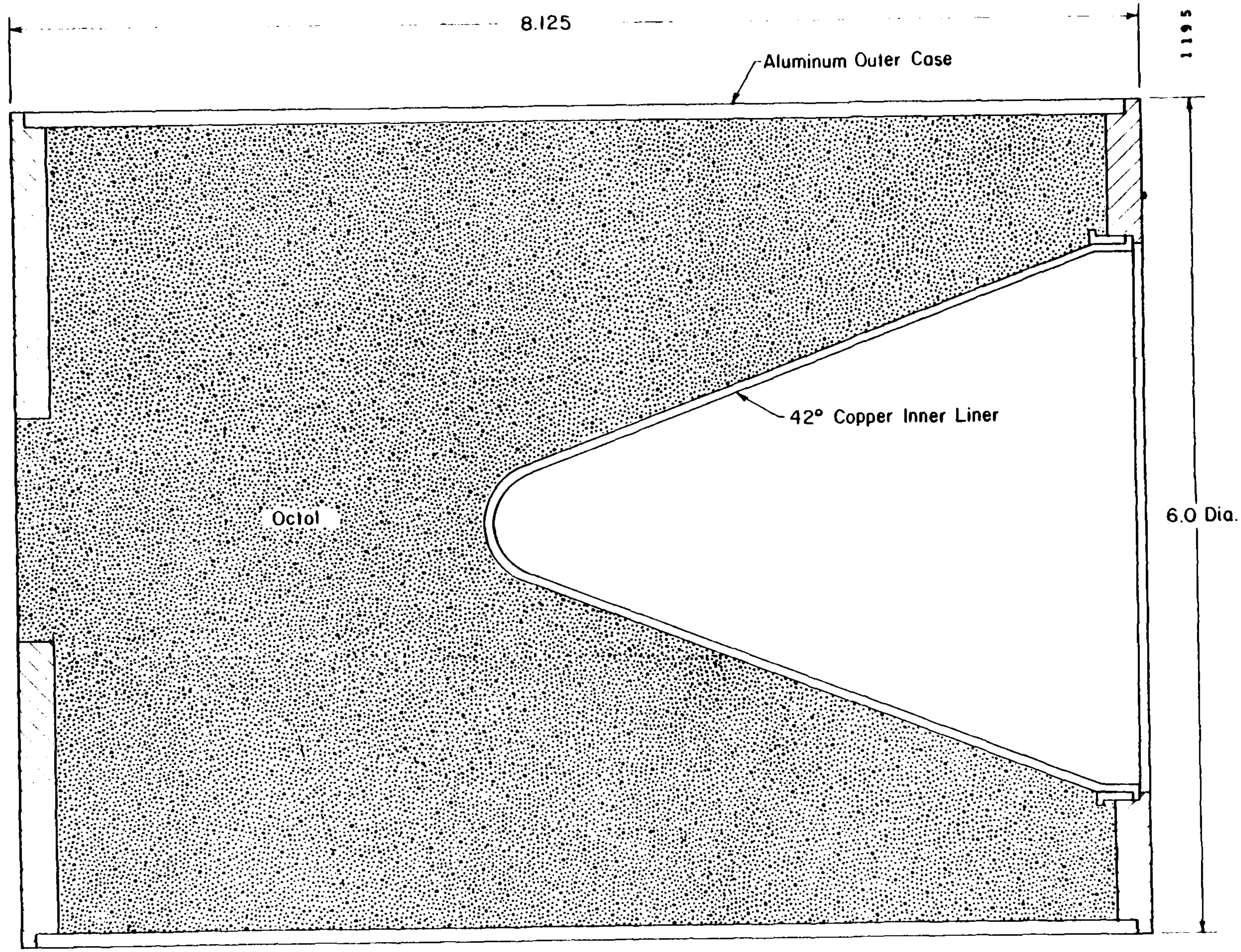

Figure 11 Shot 131-5, DRAGON Modified with Additional Octol Tamping

Shot 131-6

This shot which used a 1.6 cm thick metal containment surrounding a 1.5 Kg (nominal 3.5 lb) Octol explosive charge was loaded by FMC-Hollister. The geometry of this run is given in Figure 12. Its purpose was to provide data on the performance of the FMC baseline round modified by a thicker metal confinement.

The target rod, grid and range grid spacings were also identical with Shot 131-1.

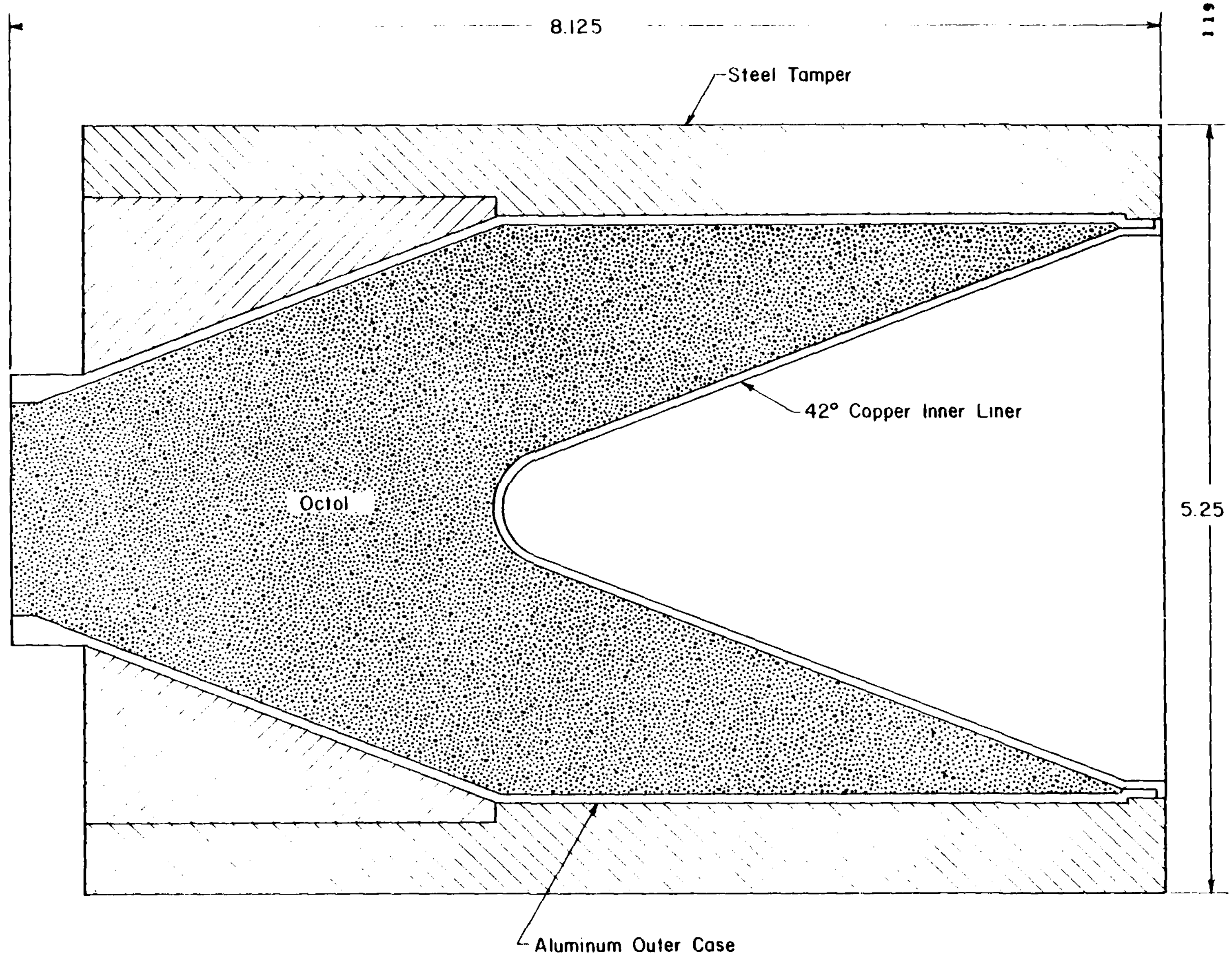

Figure 12 Shot 131-6, DRAGON Modified with Steel Tamper

Shot 131-7

This shot was a repeat of the Firestone loaded "baseline" Shot 131-1 to compare and allow assessment of the scatter in the penetration results of the baseline configuration.

The target, rod grid and range grid spacings were identical with Shot 131-1. The geometry was identical with Figure 8.

3.3 Description of the Diagnostics

The diagnostics for each experiment consisted of three 60 Kev "Cobra" flash x-ray photographs of the jet, taken at different times into the flow, and a single 1 MeV flash x-ray photograph taken of the collapse process. The 60 Kev x-rays because of their limited penetration capability show essentially a shadowgraph of the high velocity jet and permit assessment of the jet character and behavior.

The 1 MeV flash x-ray because of its penetration capability is used to stop the "action" of the liner collapse, and hence permits diagnosing the character and nature of the dynamics of the liner collapse. In addition, it shows some details of the expanding HE through density changes and permits qualitative description of the processes governing the expanding HE gases.

The 1 MeV x-ray head was mounted normal to the warhead centerline and 10 cm behind the front face of the warhead. The 60 Kev heads were mounted at different elevations but look normal to the jet centerline. This permits 3 separate and distinct non-overlapping photographs of the jet at different azimuthal angles. The center Cobra head is 183.8 cm from the jet centerline. The top Cobra is displaced 23° and is 191.8 cm from the centerline. The bottom Cobra is displaced 23° below the first and 193.7 cm from the jet centerline. This point should not be overlooked in examining the photographs and misinterpreted as apparent rotation of the jet.

The 60 Kev x-ray heads were located approximately 89 centimeters from the blast shield hot side or nominally 104 centimeters from the warhead front face.

A five centimeter grid (dot) spacing is flashed on the photographic plates shortly before firing to provide distance and magnification calibration. The grid is placed on center-line for this purpose and removed prior to firing. A sample of the grid pattern is shown in Figure 13.

Six 15.24 cm diam., 15.24 cm long (6 inch diamter, 6 inch long) 4340 (BHN 320) steel target blocks were placed on the range centerline 203.2 cm (80 inches) from the warhead front face at 20 cone diameters standoff distance (CD = 4.0 inches). The total target depth was 91.44 cm (36 inches). The first grid mark (:) was placed 50 centimeters from the warhead front face. From previous work at Firestone, these target blocks were deemed adequate for the task at hand.

Times of each x-ray pulse as measured from an arbitrary laboratory initial time were recorded to provide a time reference for interpreting the data.

A precise knowledge of distance along the range and precise times of arrival (time of flash x-ray's) permit an accurate assessment of jet velocity. By following the jet tip or each individual mass group a velocity can be determined for the entire jet if required.

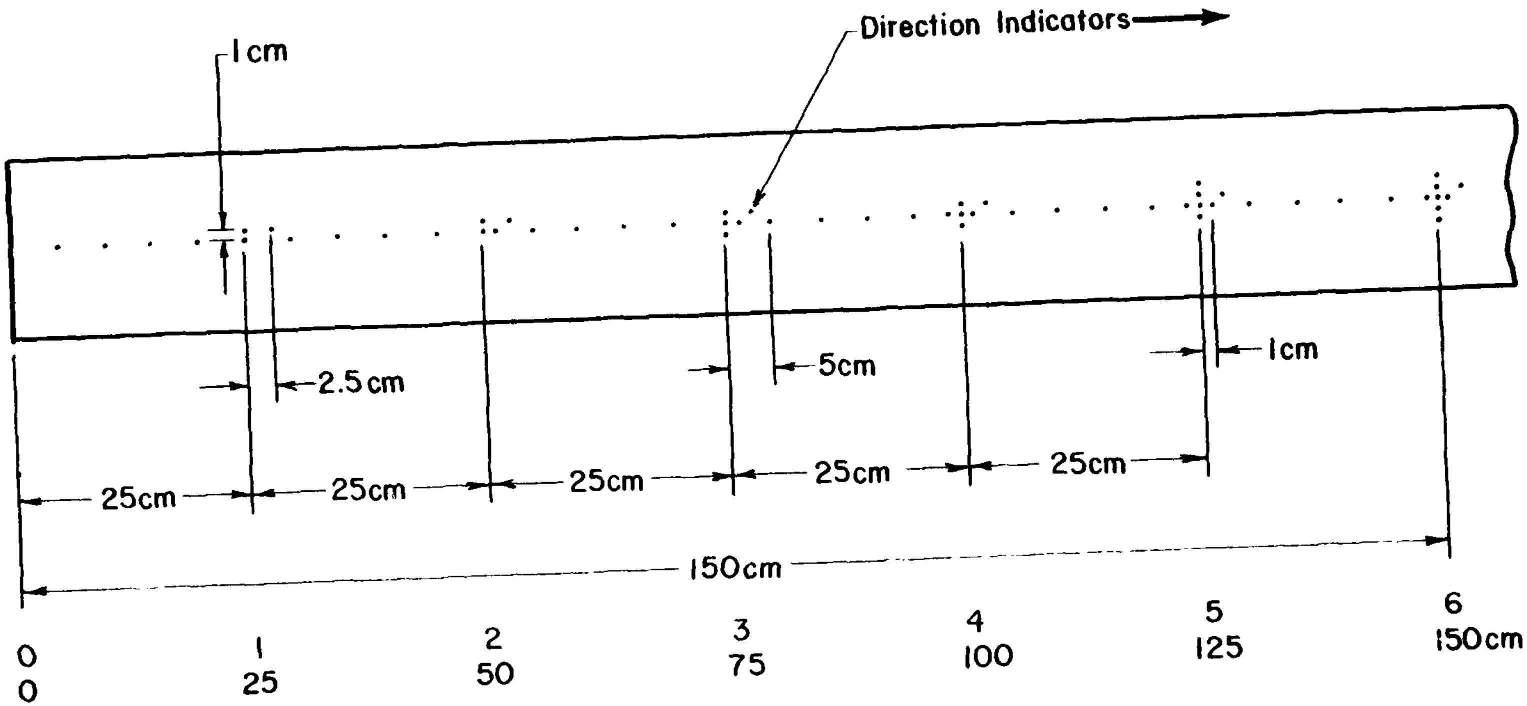

Figure 13 Grid Pattern for Cobra X-Ray Photographs

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As the aerodynamic drag at 1 atmosphere is not significant because of the high areal densities involved, the velocities are nominally constant over the distances of interest and a 2-velocity point (i.e. 3 distance-time points) is sufficient to assess jet velocity.

If required, jet mass can also be determined by assuming axial symmetry of the jet and integrating the profiles of the photographs. As can be appreciated the error involved in this measurement is greater than the velocity measurement.

Finally jet kinetic energy can be determined from combining the above and should be directly related to hole volume measurements provided target strength effects do not dominate. The ratio of jet energy to initial explosive energy is a direct measure of the efficiency of the energy transfer process in the warhead.

4. RESULTS AND CONCLUSIONS

The timing information necessary for interpreting the flash x-ray photographs is tabulated in Table 3 which includes timing for both the 1 MeV x-ray and Cobra x-rays as well as penetration and hole volume data.

Each shot will be discussed in turn, first with particular note of the specific results and exceptions to the norm and afterwards data for the series are compared.

TABLE 3

TIMING AND PENETRATION RESULTS

Shot Number	Time for 1 MeV (μsec)	Cobra 1 (μsec)	Cobra 2 (μsec)	Cobra 3 (μsec)	Penetration (at 80")	Hole Volume
131-1	26.67	147.14	167.24	187.41	12 3/8 in	N/A
131-2	28.72	145.2	170.4	195.4	9 1/8 in	126 cc
131-3	32.90*	145.2	170.2	195.5	11 1/2 in	66.8 cc
131-4	29.0	145.0	170.2	195.2	1 in	two small holes 2.5 cm
131-5	--	145.2	170.3	195.3	12 1/2 in	N/A
131-6	--	145.2	170.3	195.3	12 7/8 in	N/A
131-7	36.9*	145.0	170.0	195.0	12 3/8 in	130.4 cc

* indicates fired later than programmed

4.1 Results of Each Run

Shot 131-1

Shot 131-1 was carried out as planned. The 1 MeV and Cobra x-rays occurred at 26.67, 147.14, 167.24 and 187.41 microseconds respectively, relative to Shot CDU.

The 1 MeV x-ray photograph is shown in Figure 14. It can be seen that the collapse process has a high degree of cylindrical symmetry and the jet tip (clear on the original negatives) is beginning to emerge from the cone collapse apex. No hint of minor asymmetries is evident from this early photograph.

The three Cobra x-ray photographs are shown in Figure 15. One should note the bulbous tip on the jet, characteristic of cone collapse with initially inverse velocity gradients. The first mass elements tend to have a lower velocity than the bulk of the jet and cause a bunching up of these elements into a bulbous tip. The photographs do show a small asymmetry of the jet tip and that the jet has begun to break up by 147 μ seconds into the flow.

From this evidence, one would expect reasonably good penetration of the targets. The resulting penetration at a standoff of 80 inches (203.2 cm) can be seen from the photographs of Figure 16. A scale calibrated in inches is included in the figure. The coherent jet penetrated through two target blocks and an additional 0.95 cm (.375 inches) into a third. As the first target block experienced separation of several large pieces, no accurate target volume values could be obtained.

This shot was to serve as the baseline shot for the remainder of the experiments.

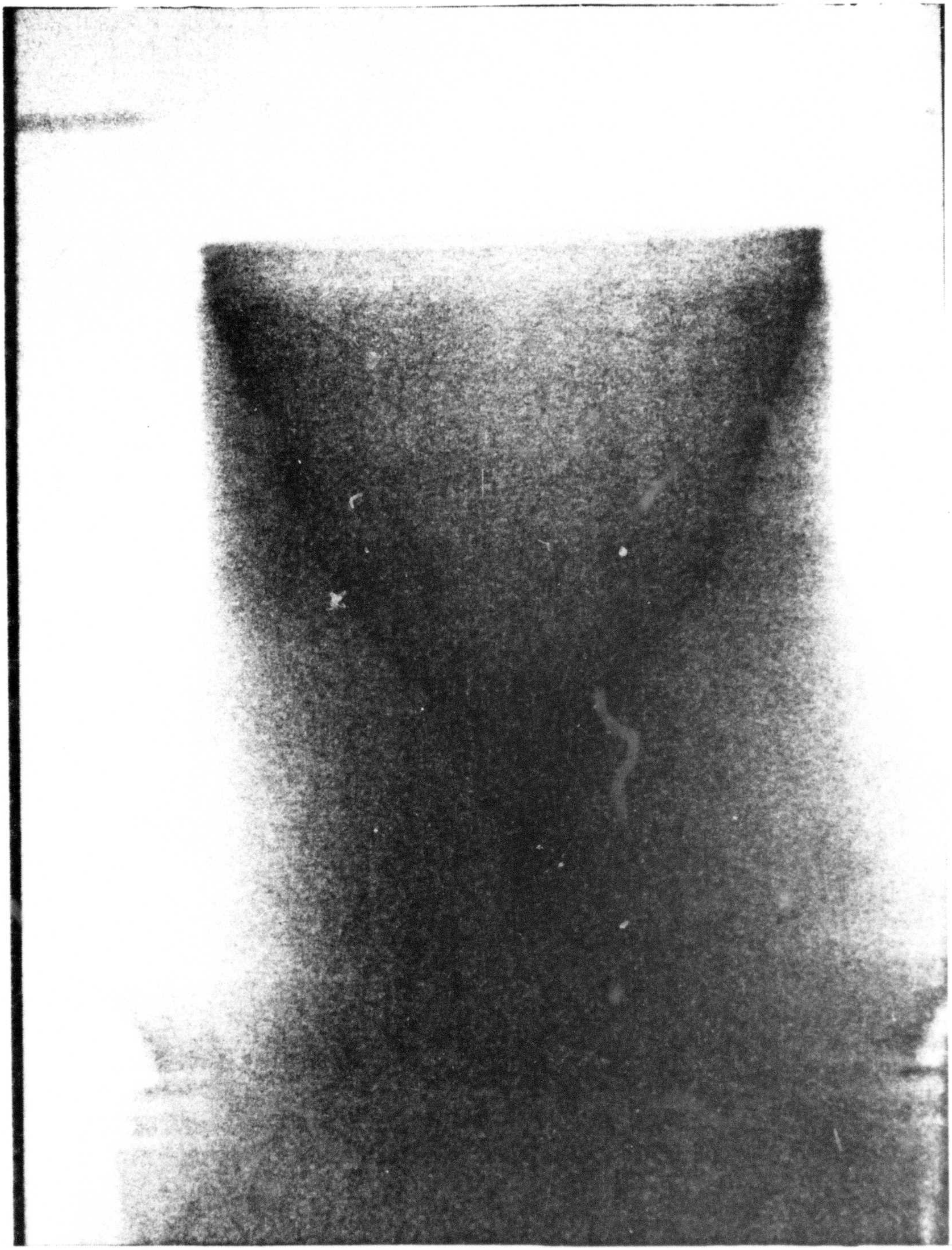

Figure 14 1 MeV X-ray Photograph of Shot 131-1

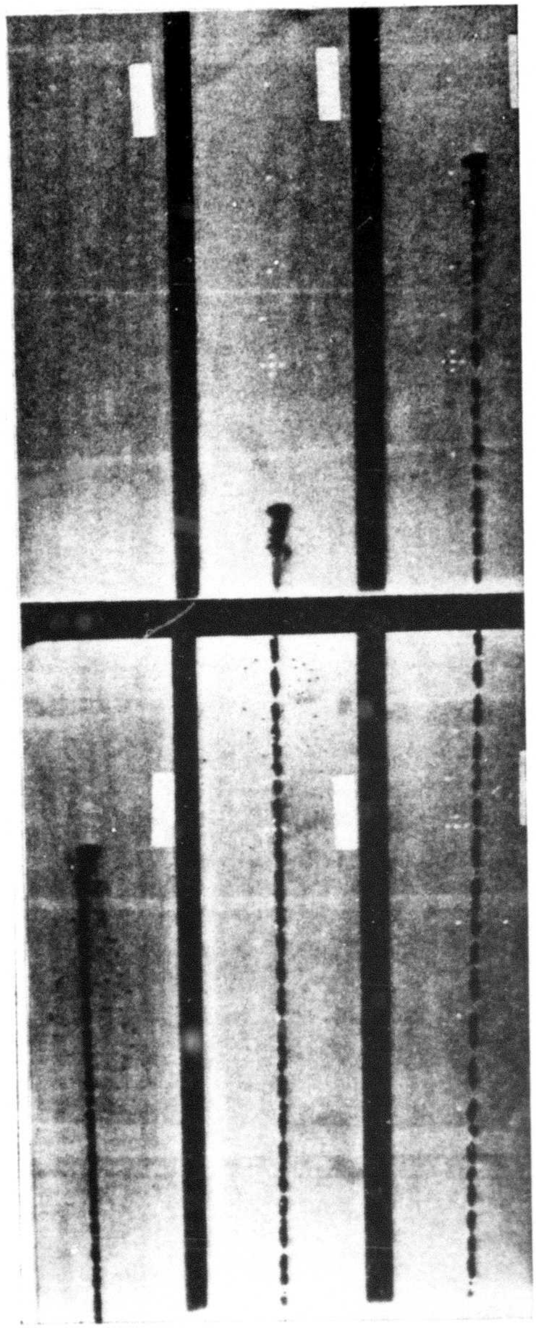

Figure 15 Cobra X-ray Photographs of the Jet from Shot 131-1

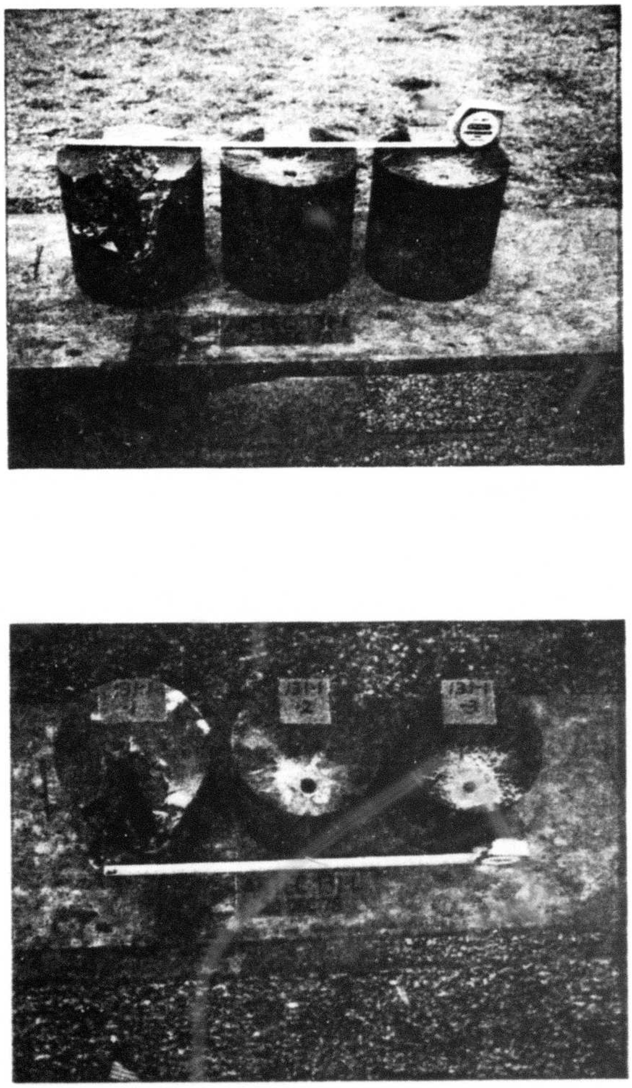

Figure 16 Photographs of the Penetration of the Target Blocks for Shot 131-1

Shot 131-2

This shot, a duplicate of 131-1 was loaded by FMC Corporation and was a measure of their loading operation. The 1 MeV flash x-ray occurred at 28.72 microseconds and the three Cobra events occurred at 145.2, 170.4 and 195.4 microseconds respectively.

The 1 MeV x-ray photograph is shown in Figure 17. It can be seen from the photograph that the collapse process also has a high degree of cylindrical symmetry. The jet tip (clearer on the original negatives) is beginning to form in the cone apex and is very symmetric about the liner axis. As the 1 MeV x-ray was taken later in time than the baseline Shot 131-1 the planned direct one to one comparison with 131-1 was not possible.

The 3 Cobra x-ray photographs of the resulting jet are shown in Figure 18. One notes again the characteristic bulbous tip with some debris immediately behind it. The tip is somewhat unsymmetric and apparently has a small radial velocity component that is increasing the tip asymmetry with time. It should be appreciated that in the prototype target condition the standoff distance is much less and the asymmetries less important. As previously, the jet has begun to break up at 145 μseconds, but retains its axial symmetry.

One would expect that the asymmetries of the tip would result in less penetration than Shot 131-1 and indeed the jet penetrated the first target block and only 7.94 cm (3.125 inches) into the second for a total penetration of 23.18 cm (9.125 inches). The hole volumes in target blocks 1 and 2 were 110 cc and 16 cc respectively for total hole volume of 126 cc.

We would conclude from this shot that the FMC loaded device was not as efficient a penetrator as the Firestone loaded warhead by a factor of 0.74, although the specific reason for this difference is not apparent from the limited data.

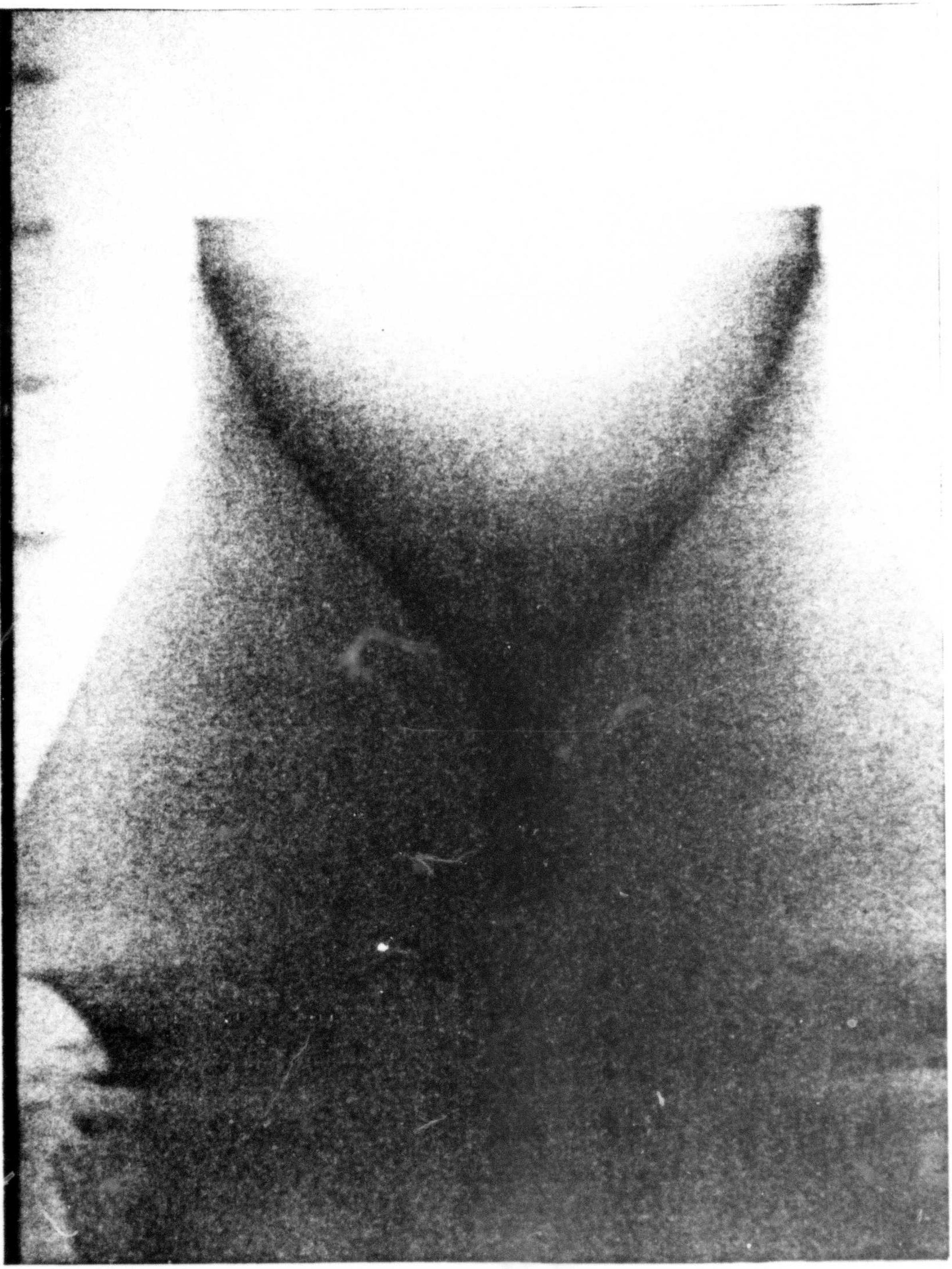

Figure 17 1 MeV X-ray Photograph of Shot 131-2

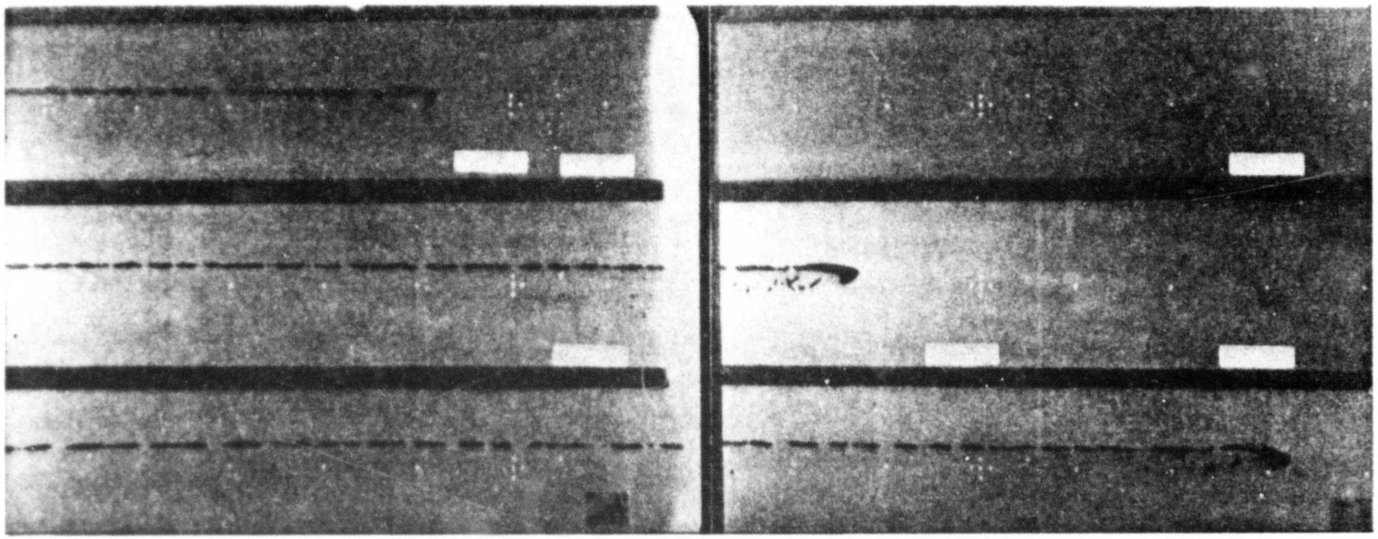

Figure 18 Cobra X-ray Photographs of the Jet from Shot 131-2

Shot 131-3

This shot investigated the effect of a 2 layer geometry with TNT as the outer layer. The 1 MeV x-ray occurred 4.9 microseconds later than programmed (28 microseconds) at 32.9 microseconds. The three Cobra x-rays occurred at 145.2, 170.2 and 195.5 microseconds respectively.

The 1 MeV x-ray photograph is shown in Figure 19. It can be seen that because of the unplanned delay that the collapse process has progressed further along the liner. Some slight asymmetries in the jet tip can be seen at this early time but the tip radial velocity asymmetry is relatively small.

Figure 20 shows the 3 flash x-ray photographs. The jet including the tip is symmetric well downstream of the charge and orderly break up has begun to occur at 145.2 microseconds.

From this symmetric jet behavior one would expect good target penetration and indeed the measured target penetration was 29.2 cm (11.5 inches) or just slightly short of defeating two six inch target blocks. As the holes did not break out to the target block side faces, the hole volume could be measured and was determined to be 46.4 cc and 20.4 cc respectively for a total of 66.8 cubic centimeters. From a comparison of this run with 131-2 the FMC baseline we note that the target penetration has increased 26% over the baseline but that the hole volume has decreased 47% over the baseline value. Compared with the Firestone baseline we note a 7.1% decline in penetration and a 49% decline in hole volume. We do not favor the latter comparison since it involves two separate loading facilities and it is known that the results obtained from similar devices loaded at different facilities are not necessarily the same.

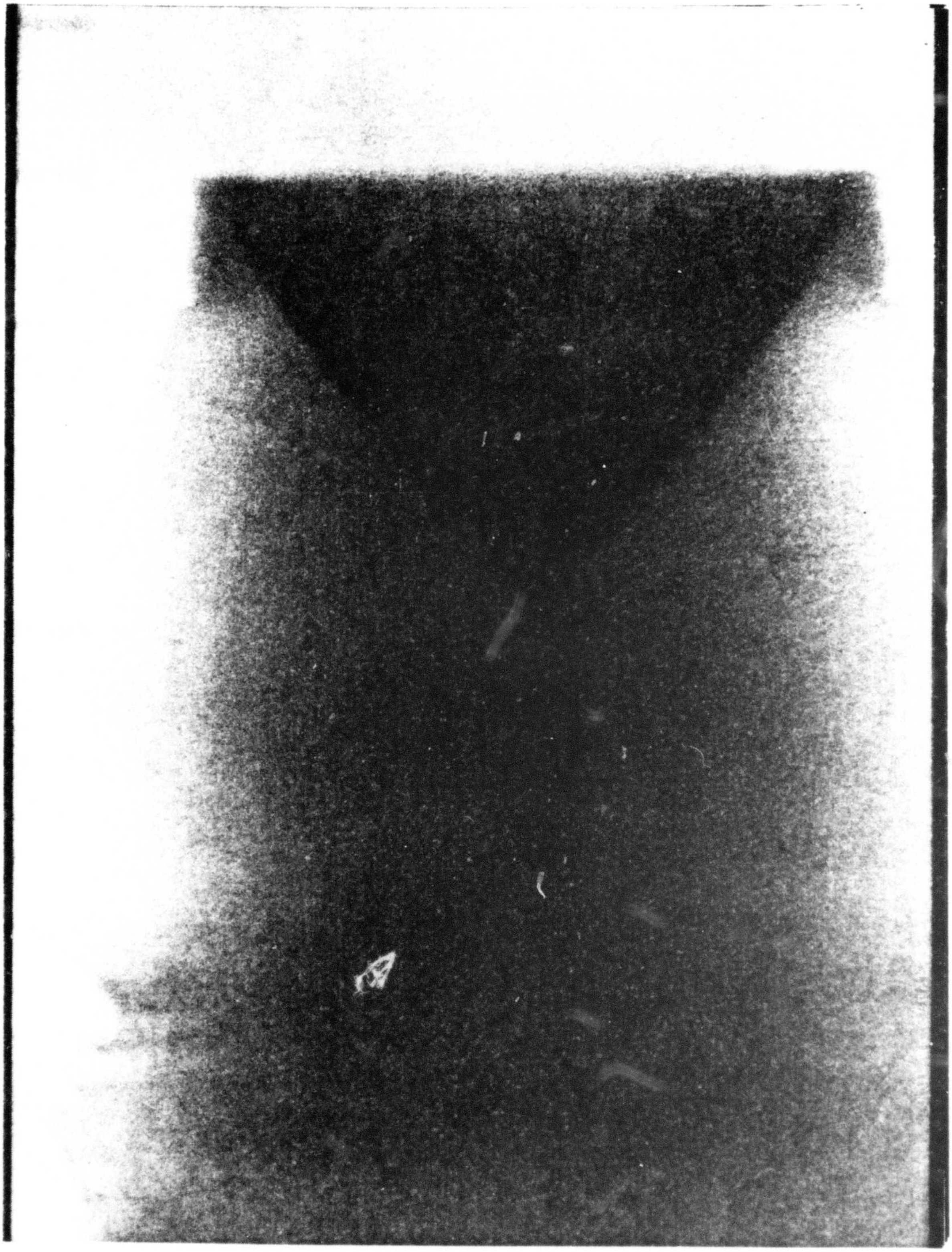

Figure 19 1 MeV X-ray Photograph of Shot 131-3

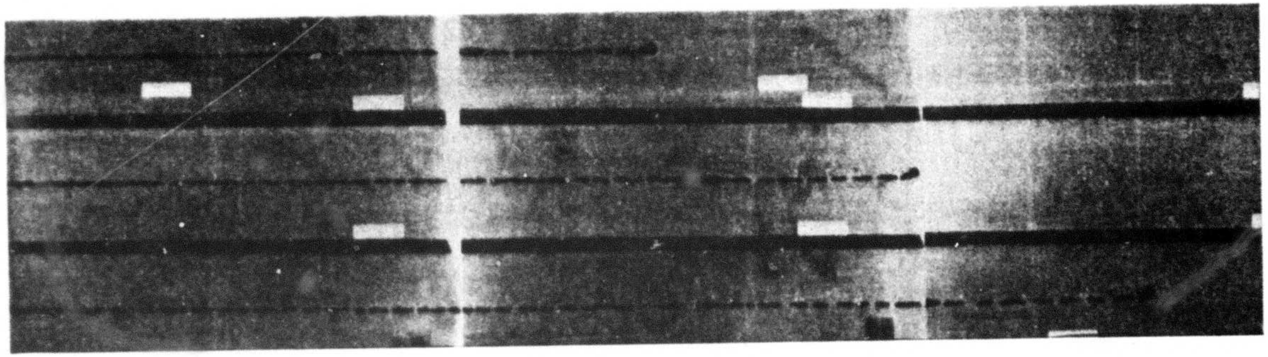

Figure 20 Cobra X-ray Photographs of the Jet from Shot 131-3

Shot 131-4

Shot 131-4, another 2 layer geometry shot with Baratol as the outer layer was carried out on 3 January 1979 without diagnostic problems. The 1 MeV flash x-ray occurred as planned at 29.0 microseconds. At this time the jet tip is observed to be formed and to be symmetric about the liner axis as seen in Figure 21.

The three Cobra flash x-ray photographs shown in Figure 22 were taken at 145.0, 170.2 and 195.2 microseconds reveal a strikingly different picture from the previous three runs. The jet is completely fragmented with gross asymmetries evident from the trajectories.

This result was completely unexpected, but in retrospect might have been predicted had the clues evidenced in the 1 MeV "no flow" x-rays been seen. Each warhead was x-rayed using the 1 MeV machine prior to actual firing. The "no flow" photograph serves three purposes, (1) to assure that the x-ray is functioning and that the densities of device, protective metal cannister and flourescent screens are all in order, (2) to provide a direct print of the initial geometry for baseline measurement purposes and (3) to establish the degree of uniformity of the explosive casting.

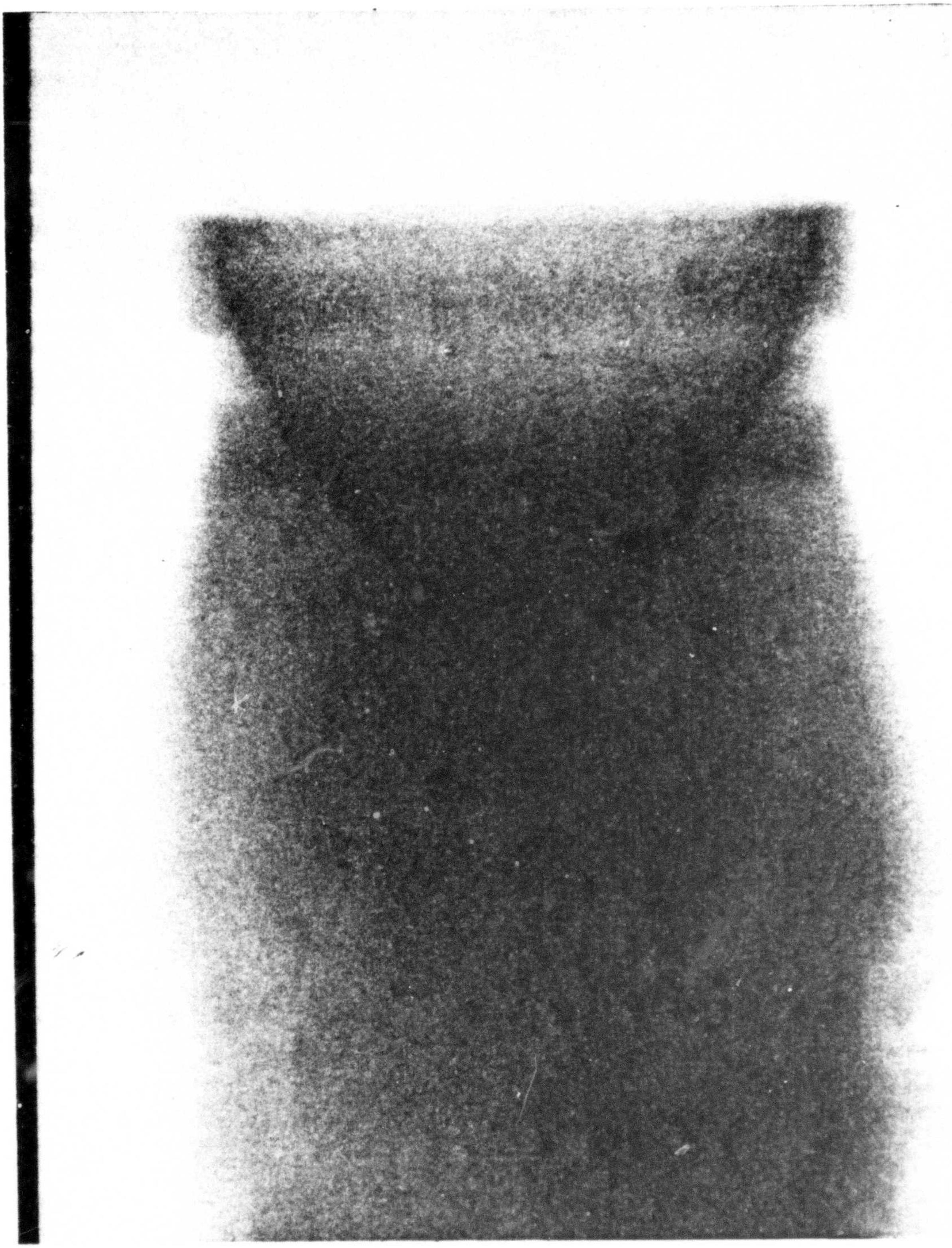

Figure 21 1 MeV X-ray Photograph of Shot 131-4

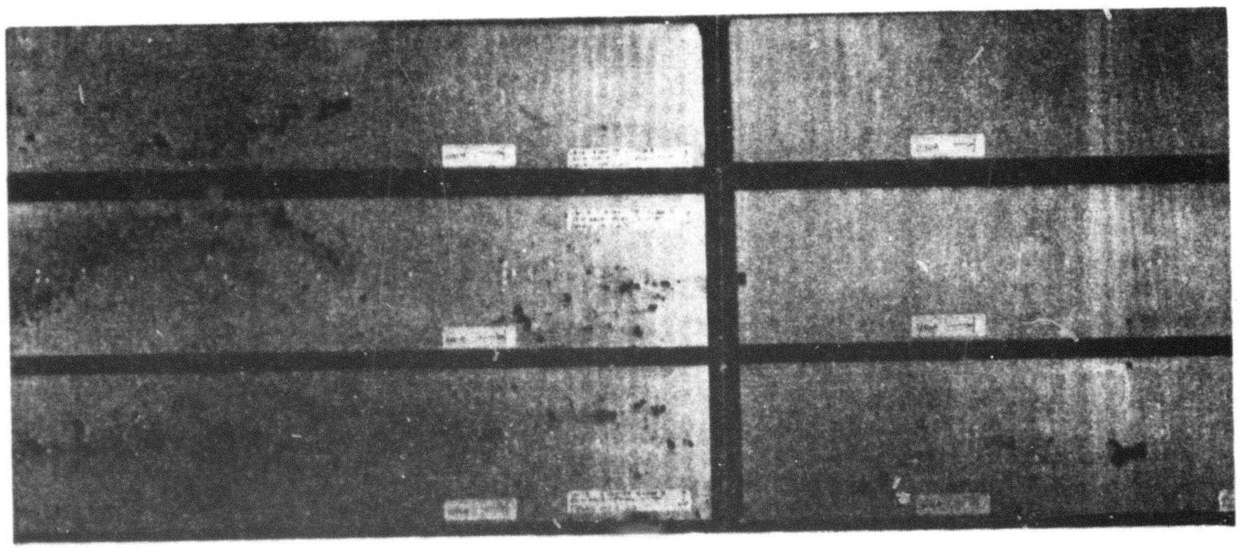

Figure 22 Cobra X-ray Photographs of the Jet from Shot 131-4

The "no flow" photograph is included as Figure 23. On very careful inspection one can note a series of different density zones near the base end of the warhead. The first zone is caused by the additional mass of the step in the metal outer liner, and is evident in all of the other no flow photographs. Following these are two additional rings, first a lighter zone (in the negative) followed by a darker zone. The remaining volume has a somewhat mottled look implying either poor developing procedure for the film or non-uniform density in the explosive load.

We hypothesize that the rings are a layer of Octol overlaying a layer of Baratol. We reason that the melting points of the two explosives, 70-80°C for Baratol and 79-80°C for Octol and the requirement that the Baratol be above the liquification temperature in order to pour easily combined to produce a situation wherein the hot Baratol being poured into the warhead melted the inner Octol liner, ran down the cone and stratified at the bottom. Additionally the hot Baratol scoured the Octol inner layer destroying the symmetry of the charge. Indeed a close examination of Figure 21 shows asymmetries in the flow photograph particularly in the outer edge of the expanded flow. The origin of these asymmetries we believe to be a non uniform casting of the two layered explosive.

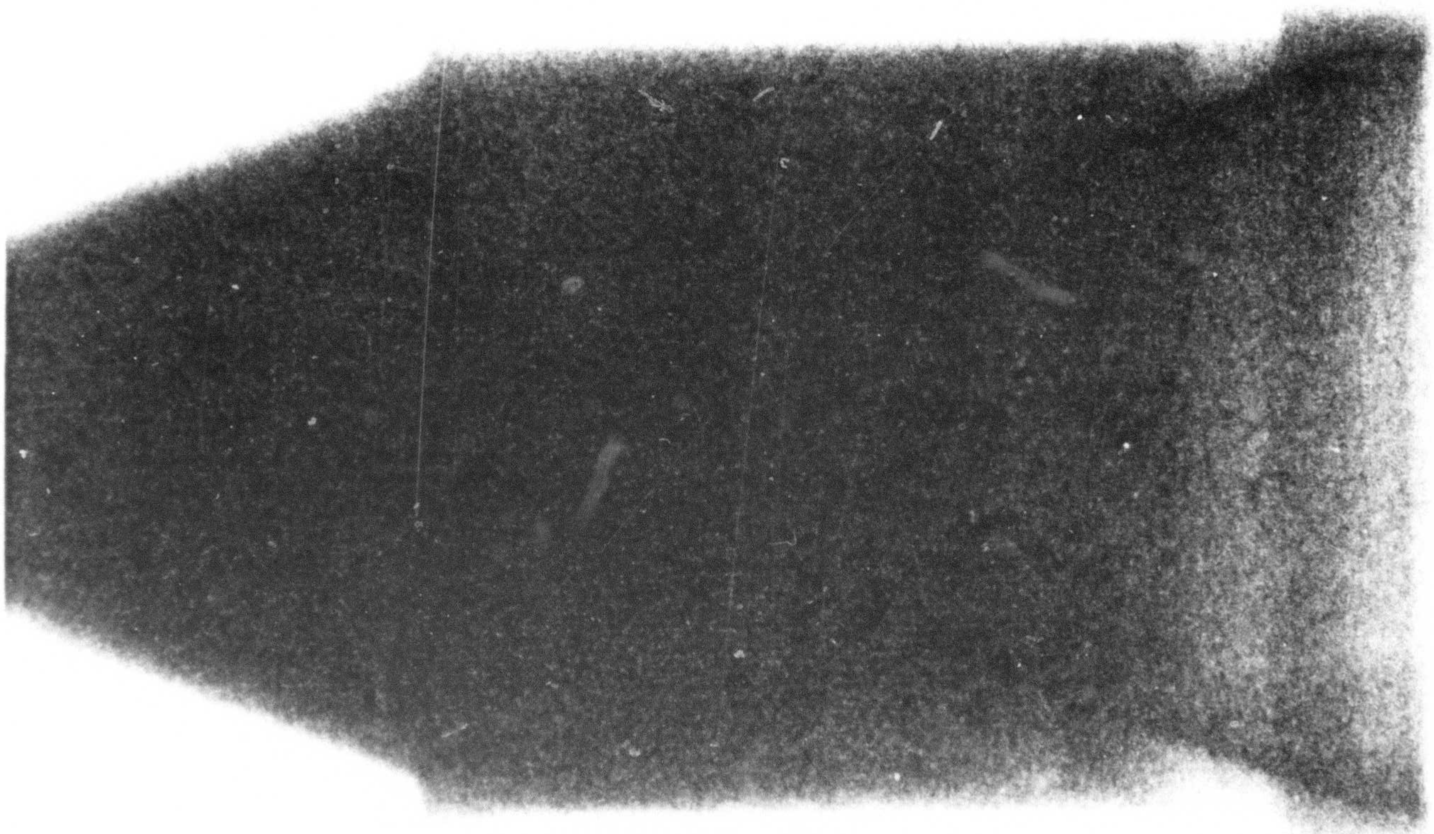

Figure 23 1 MeV X-ray Photograph of Shot 131-4 (no flow)

Since a high degree of symmetry of the loaded device is required, indeed ultra precision in the case of high performance so-called "precision" shaped charge devices, the origins of the highly fragmented jet become clearer. Essentially, the poor results of the shot were preordained by the poor symmetry of the explosive loading.

The target plates as might be expected, evidenced only 2 small holes 2.5 centimeters deep and extensive pitting over the entire face from the high velocity debris. The only significant penetration should be attributed to the short jet tip which apparently was the only part of the jet to retain any degree of symmetry.

Shot 131-5

For 131-5, the HE tamped warhead, the three Cobra x-ray events occurred at 145.2, 170.3 and 195.3 microseconds respectively. The three Cobra x-rays of the jet are shown in Figure 24.

As the ratio of C/M, i.e. explosive mass to liner mass, for this warhead varies less than the other shots, the jet velocity gradient is much smaller, consequently the jet does not stretch and a more "projectile" like jet is formed. In principle, for constant C/M in a tubular geometry, the resulting jet length is equal to the original liner length. This basic point often overlooked in shaped charge work is demonstrated here.

For purposes of this present study this result is superfluous but it is valuable to note that this high velocity projectile having a mass of approximately 40 grams and moving at 9.5 Km/sec has a considerable amount of jet energy (nearly 10% of the explosive energy).

The jet penetrated two target blocks and 1.27 cm (.5 inches) into the third block for a total of 31.75 cm (12.5 inches). The first block was fractured and separated out to the side surfaces and a volume determination was not possible.

The shot does demonstrate that significant penetration improvement (37%) is possible using an increased amount of Octol. In addition, the energy delivered to the target was significantly increased in this design as evidenced by the complete lateral failure of the first target block. For some applications, this design approach may be worthy of consideration.

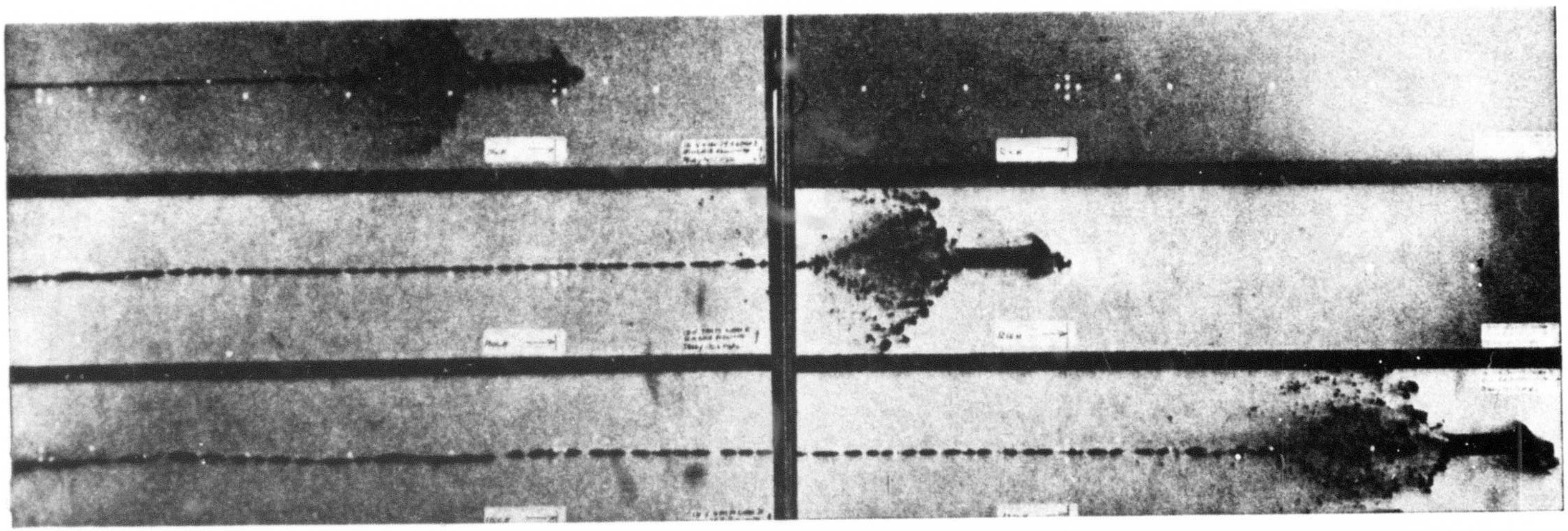

Figure 24 Cobra X-ray Photographs of the Jet from Shot 131-5

Shot 131-6

This shot used massive steel confinement to demonstrate the effect of delaying the arrival of the later rarefaction. The three Cobra x-ray devices were fired at 145.2, 170.3 and 195.3 microseconds respectively and good data was obtained.

The slight asymmetries in the jet tip seen in Figure 25 that were also in evidence in Shots 131-1, 131-2, and 131-3 are also evident here, although jet break up is not seen until 170 microseconds into the flow. This in turn can be expected to yield greater penetration and indeed total penetration was (12 7/8 inches) 32.70 cm, the largest produced during the investigation. The jet penetrated two blocks and 7/8 inches into the third. The first block was cracked and separated so that a volume measurement could not be made.

The shot did demonstrate that the penetration could be increased 40% but at an increase in confinement weight of 24.8 pounds (11.3 Kg).

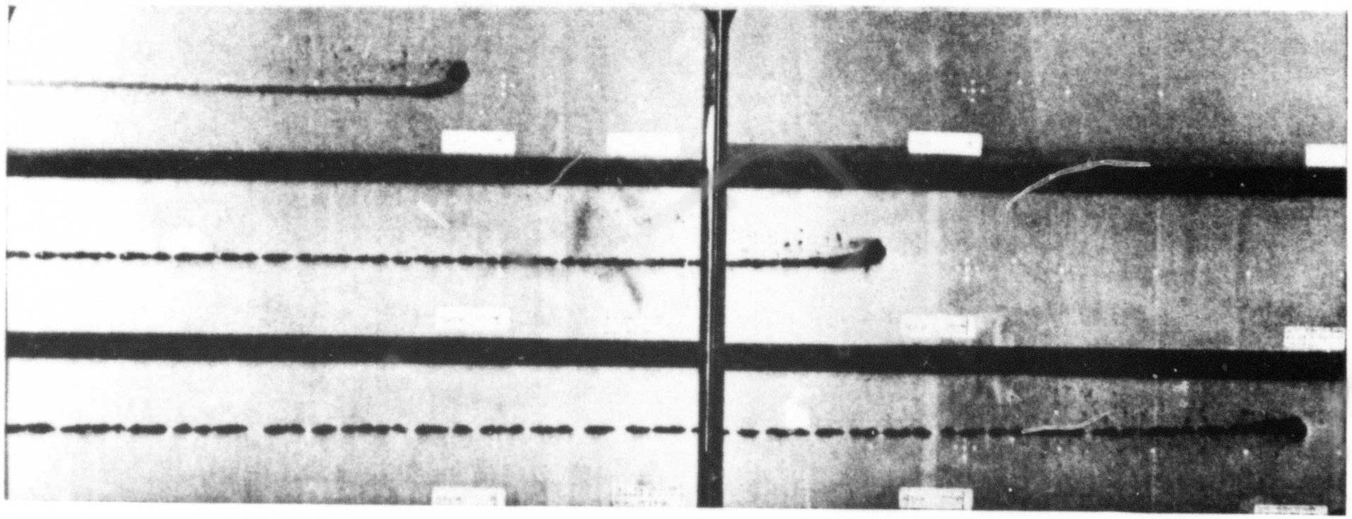

Figure 25 Cobra X-ray Photographs of the Jet from Shot 131-6

Shot 131-7

Shot 131-7 was essentially a repeat of 131-1 in order to confirm that the penetration obtained in that shot was reproduceable. The 1 MeV x-ray functioned late at 36.9 micro seconds and the Cobras as planned at 145.1, 170.2 and 195.2 microseconds.

As the 1 MeV x-ray was late, the collapse shown in Figure 26 is seen just prior to the detonation wave arriving at the base of the cone. A well-formed jet tip is just emerging from the cone but even at this early stage the tip is inclined from the cone axis as was 131-1.

The three Cobra radiographs are shown in Figure 27. It can be seen that the bulbous jet tip remains slightly skewed during its transit along the range but the remainder of the jet remains colinear.

The jet produced a penetration of 31.4 cm (12-3/8 inches) and confirmed the results of Shot 131-1. We also obtained a hole volume measurement for this shot--130.4 cubic centimeters. We conclude from this result that the Firestone loaded warheads are statistically similar and that the FMC loaded device provides less performance for undetermined reasons.

One might note in passing that greater penetrations could be expected if the tip asymmetries could be reduced and the energy deposited at a specific point on the target rather than distributed over the target face.

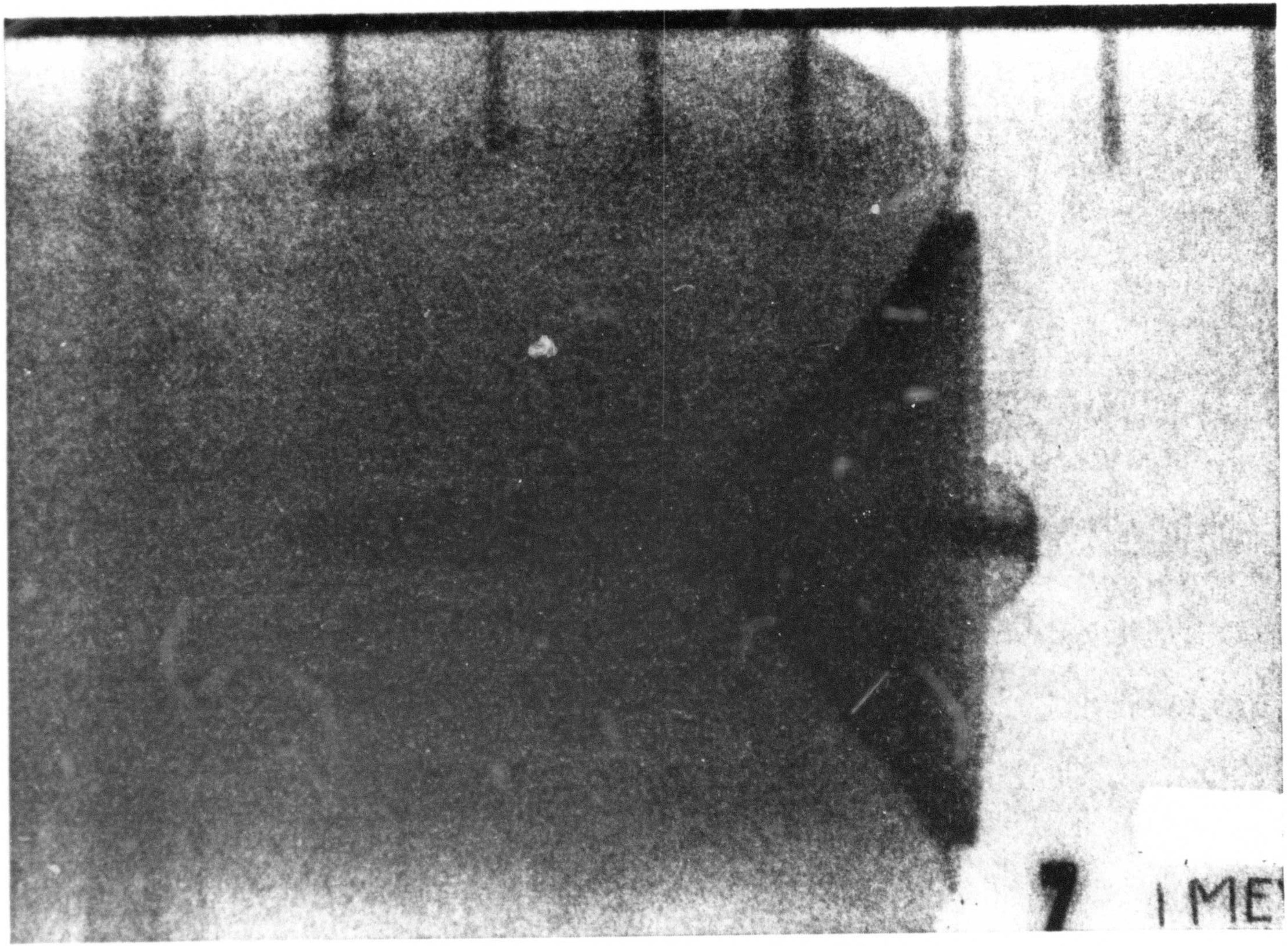

Figure 26 1 MeV X-ray Photograph of Shot 131-7

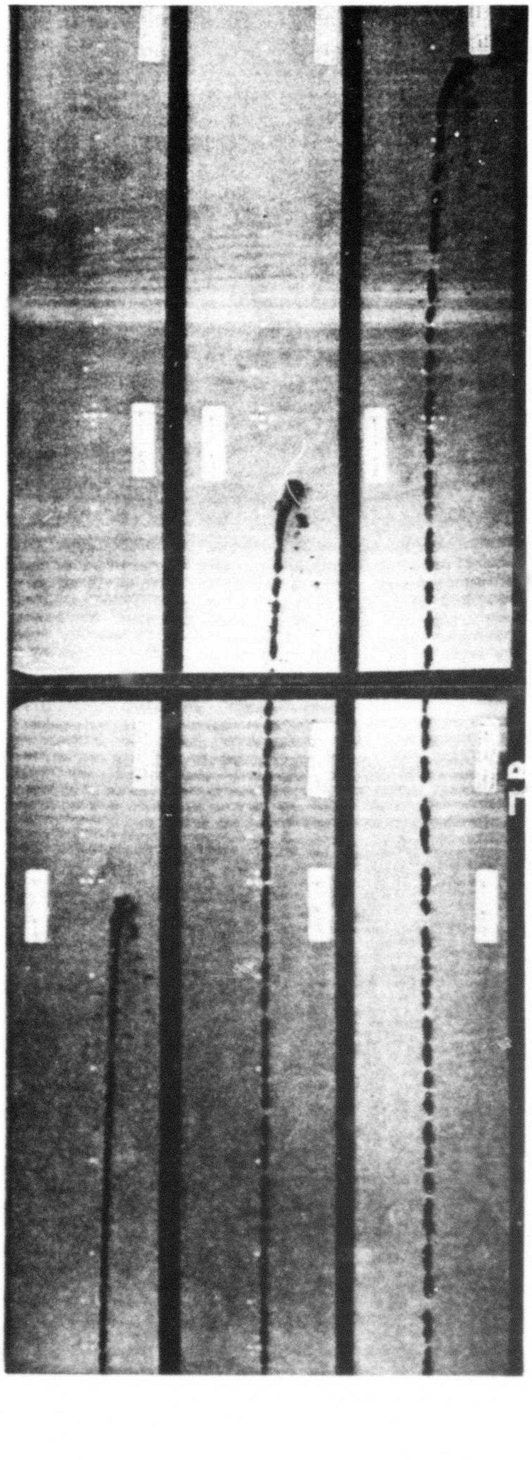

Figure 27 Cobra X-ray Photographs of Jet from Shot 131-7

As target hole volume data was obtained for only two of the experimental rounds and the FMC loaded baselines, analysis of target hole volume was not performed.

4.2 Discussion of the Results

Despite triggering problems with the 1 MeV flash x-ray system, which yielded photographs at slightly different times than preselected, the fracturing of target blocks, and casting problems in one round, the data yield from the test series was generally very good and a number of conclusions can be made from the available data.

Pivotal in the analysis of the data is the selection of a baseline run. It was our original intent to use the Firestone loaded warhead for this purpose, with a check using an otherwise identical FMC loaded device for confirmation. As the FMC device gave substantially different penetration and FMC's facilities loaded all of the experimental configurations, it was felt that using 131-2, the FMC loaded standard round as baseline, would be more appropriate than using the Firestone loaded baseline round.

The test series demonstrated conclusively the improvement possible using heavy steel confinement. Shot 131-6, the steel tamped round, gave 41% greater penetration than the FMC baseline round. Such improvement is well-known in the field but impractical for prototype warheads since it required nearly 25 additional pounds of mass to produce this improvement.

The test series demonstrated the improvement possible using massive additional explosive to provide confinement. Shot 131-5, the 10 pound Octol run, succeeded in increasing penetration by 37% over the FMC baseline round. Again, some improvement is to be expected since it required nearly 3 times the explosive to accomplish this improvement in penetration.

It is worthy of note however, that the overall energy conversion from chemical explosive energy into jet kinetic energy was nearly 10% and could perhaps be further improved. The additional explosive serves to add mass and energy to the jet, a fact that can be important in some applications.

The test series verified that lateral surface rarefactions are of great importance in jet formation and that active tamping using TNT as the outer layer can improve the penetration performance of the round. Shot 131-3, which used the same explosive weight as the FMC baseline round but used a TNT outer layer as an active tamper, succeeded in increasing target penetration by 27%.

The additional verification Shot 131-4, using a Baratol/Octol load, malfunctioned due to loading asymmetries and is not available for comparison.

Overall we would conclude that using self consistent data, i.e. only warheads loaded by the FMC loading facility that performance improvements up to 30% can be realized using the techniques discussed in this report. If warheads loaded at the Firestone facility are used as the baseline then the experimental results are scattered and inconclusive. We favor the former since the data is self consistent and the results are in keeping with theoretical predictions.

5. RECOMMENDATIONS

The result of this series of experiments, that target penetration can be improved by as much as 30% without an increase in explosive loading, is a very important one.

However, as the data is limited to a single shot, we recommend that six additional warheads be loaded and test fired. Three should be identical to 131-3, i.e. a TNT/Octol shot to provide additional statistical verification of the result, and three loaded with Baratol/Octol to investigate if increases beyond 30% are possible using different combinations.

Beyond these experiments we would recommend an engineering effort to provide the parameters that would upgrade an existing warhead configuration, for example the Dragon Warhead. We would envision a significant analytical, 2D-hydrodynamic code effort to parameterize the task and the loading and firing of a number of optimized warheads, with off-optimum runs in addition to insure that the calculated optimum and practical optimum as indeed coincident or nearly so.

Such a modest effort would do much toward improving present antiarmor capability.

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